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APPROVED FINAL DRAFT

EXPERIMENTAL RESEARCH INVESTIGATION
OF
EXTREMELY LOW FREQUENCY PROPAGATION

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9200 East Flair Drive
El Monte, California

Contract No. AF19(628)-1603

Project No: 4603
Task No: 460305

Scientific Report # 1
SGC No. 212R-4

15 February 1963

Prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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(13) NA
(14) SRI; 212R-4

(15) Contract No. AF19{628}-1603
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ABSTRACT

Characteristics of ELF electromagnetic wave propagation were investigated by measuring the characteristics of cw signals transmitted over a 400 cps link, established between Boron, California, and Carlsbad, New Mexico, a distance of 1300 km. The work described is a continuation of the investigations carried out under AF 19(604)-7448.

Propagation measurements were carried out during July and October 1962. Signal strength, received and transmitted signal phase, and atmospheric noise were recorded. Data reduction and analysis showed that received values of signal strength were 2 db less during nighttime and 4 db less during daytime than the values predicted by analytical studies carried out during the previous contract. Data reduction and analysis of the recorded phase data showed that more stable reference signal sources are required at transmitter and receiver. The form of the record obtained over a link which had approximately a 6 db signal to noise ratio in a 1 cps band indicates that a useful technique has been evolved.

Atmospheric noise data was recorded for all transmission periods. This data is presented in the form of amplitude probability distributions and impulses per unit time distributions.

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1.0 INTRODUCTION

1.1 Purpose

This report presents some results of a continuing experimental investigation of extremely low frequency (ELF) electromagnetic wave propagation phenomena using a 400 cps transmission link. Previous research carried out under Contract AF 19(604)-7448 is reported in Reference 1, which contains background information and theoretical calculations that will prove invaluable in any study of the work to date. The work to date has been directed toward substantiation of the mode theory of VLF propagation as extended to ELF in Reference 3, and modified by changes in the ionosphere model (Reference 4) to account for increased daytime attenuation.

Experimental studies of the signal transmission environment established by the atmospheric noise are carried out by recording the impulse distribution and amplitude probability distribution of the noise.

1.2 Method of Approach

The transmitter facility and mobile receiver facility used on the previous contract were modified for use in the present program. A 1300 km transmission link was established between Boron, California, and Carlsbad, New Mexico, for measurement of transmission amplitude and phase. Additional equipment required for these studies was designed and fabricated.

1.3 Scope of Report

This report describes the equipment used, the data collection procedures; presents the data collected, and compares the test results with previous analytical studies. Field strength, transmission path phase information, and atmospheric noise data collected under both daytime and nighttime conditions in July and October 1962 are presented.

2.0 EXPERIMENTAL SETUP

2.1 Transmitter Facility

The previously used transmitter facility, located near Boron, California¹, was reactivated in the current series of experiments. The transmitter is a 400 cps, alternator with a rated output of 175 kw for continuous duty and 300 kw for intermittent duty, driven by a 350 horsepower synchronous motor. Figure 1. is a block diagram of the transmitter facility.

The 400-cycle antenna¹ employed at Boron consists of a long straight cable, laid out in the east-west direction, and supported a few inches above the ground. The ends of the cable terminate in grounding electrodes. The antenna is driven near one end. Ideally, a horizontal antenna should be several hundred miles in length to radiate efficiently at 400 cps. However, when the radiator is of necessity very short compared to a wavelength, acceptable results can be achieved by grounding the ends and making the ohmic loss component of the input power as small as possible. The radiation efficiency of a horizontal wire antenna is increased by locating over low conductivity soil.

The 10,000-foot antenna consists of 5000 feet of 72 conductor, No. 14 AWG cable in a PVC (polyvinylchloride) jacket, and a bundle of six No. 6 AWG street lighting cables, 5000 feet in length. The conductors in each section are paralleled to provide a total d-c resistance of .433 ohms. The antenna is driven through a transformer and capacitive matching network.

A network of grounding electrodes is employed at each end to make the ground resistance low and distribute the ground current over a larger area. Each ground network consists of 15-4" diameter pipes, 20 feet long, sunk vertically into the ground in 6-1/2 inch diameter holes with cokebreeze surrounding the pipe to provide electrical contact with the soil.

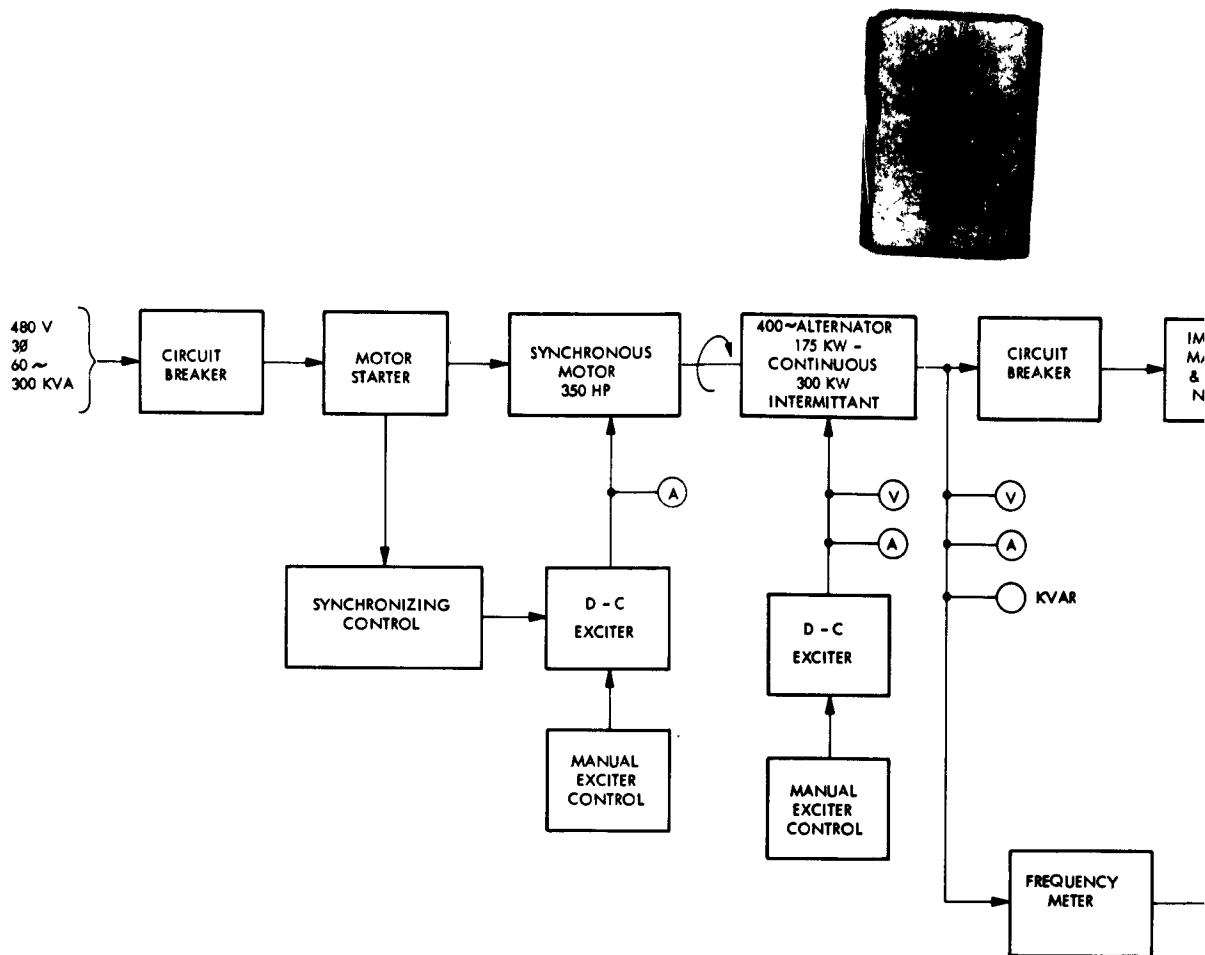


Figure 1. Transmitter Facility Functional Block Diagram

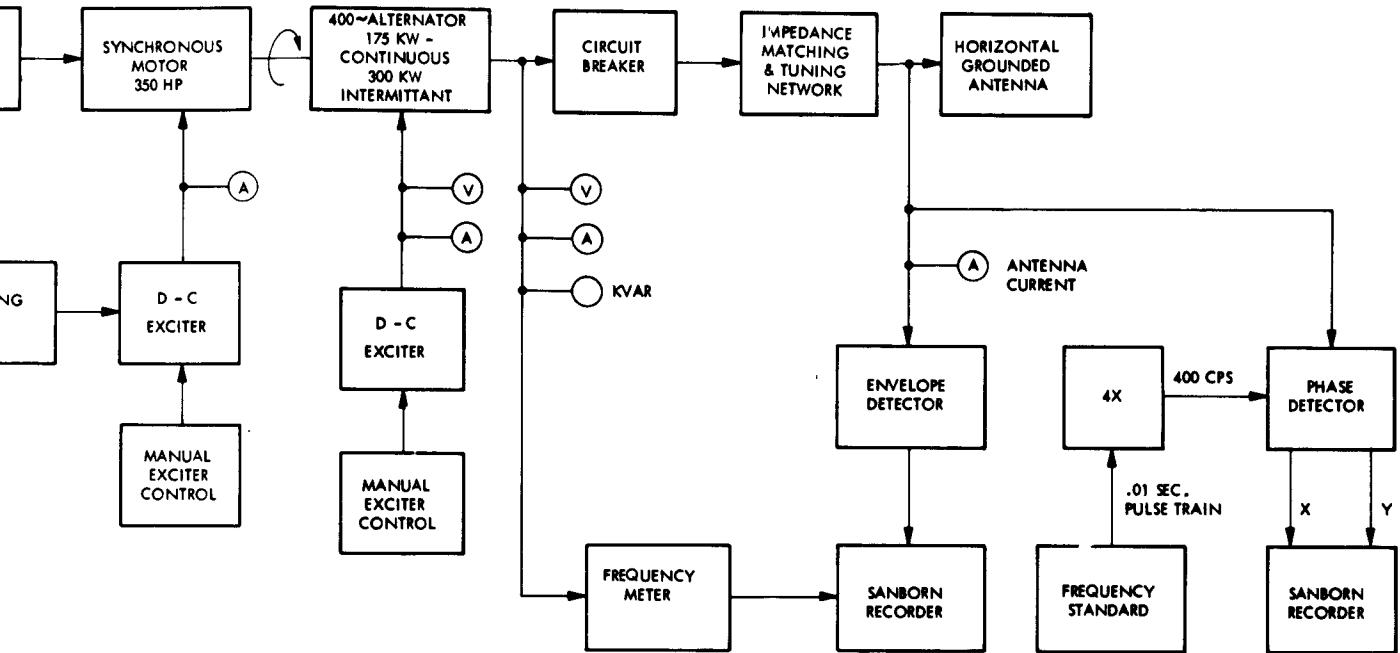


Figure 1. Transmitter Facility Functional Block Diagram

The soil in the Boron area is alluvium of recent origin which extends to a depth of several thousand feet. Two layers of saddleback basalt exist at the 500 and 1000-foot levels. The water table is 900-1000 feet.

For this series of experiments, a dual phase detector and 100 kc frequency standard, divided to 400 cps, were added to record the relative transmitter phase as shown in Figure 2. Refer to section 2.2 for further discussion of signal phase detection techniques.

2.2 Receiver Facility

The present receiver, shown in Figures 3 and 4, is basically the same equipment used in the previous series of experiments¹ with the addition of a phase-lock loop detector and associated equipment. See Figure 5.

The antenna is a 6 1/2-foot diameter shielded loop with an effective height of 2 cm, resonated at 400 cycles with a Q of 10. The 40-cycle bandwidth of the antenna and preamplifier is narrowed independently to 7 cps and 1 cps in two predetection filters, detected and recorded on a chart recorder.

A phase-lock loop detector was added with a .25 cps noise bandwidth loop filter. Figure 6 shows the interconnection of the units in the system. Figure 7 is a block diagram of the limiter amplifier used with the dual phase detector. The limiting level is set approximately 10 db above the expected signal level for the signal amplitude phase detector and approximately 10 db below the expected signal level for the feedback loop phase detector. The circuit configuration for the loop filter is similar to that employed in telemetry phase-lock receivers².

Relative received signal phase is compared with a 400-cycle crystal oscillator and recorded by reconnecting the dual phase detector as shown in Figure 8. Addition of a 7 cps bandpass filter between the limiter and the dual phase detector reduced some of the atmospheric noise.

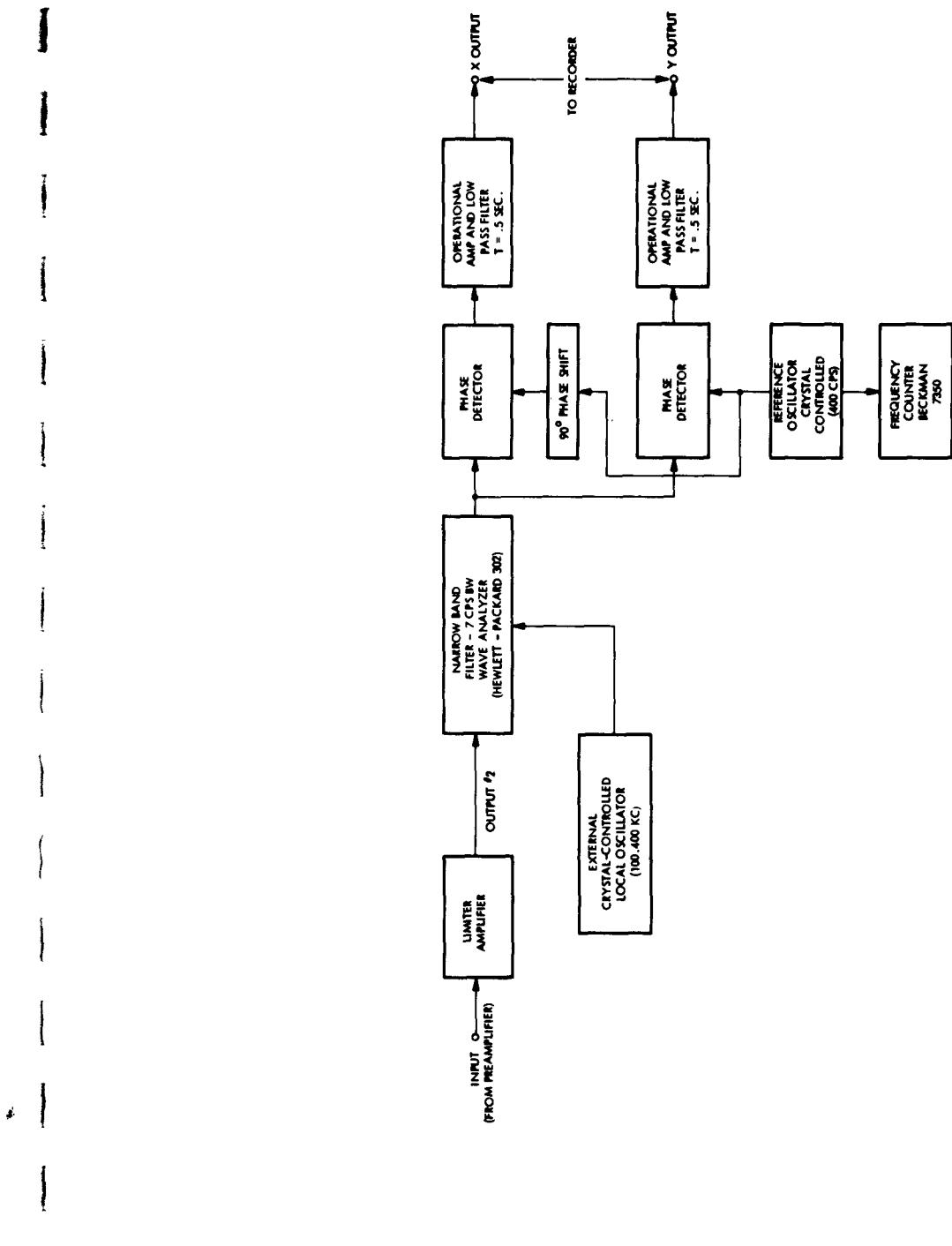


Figure 8. Receiver Phase Measurement Functional Block Diagram

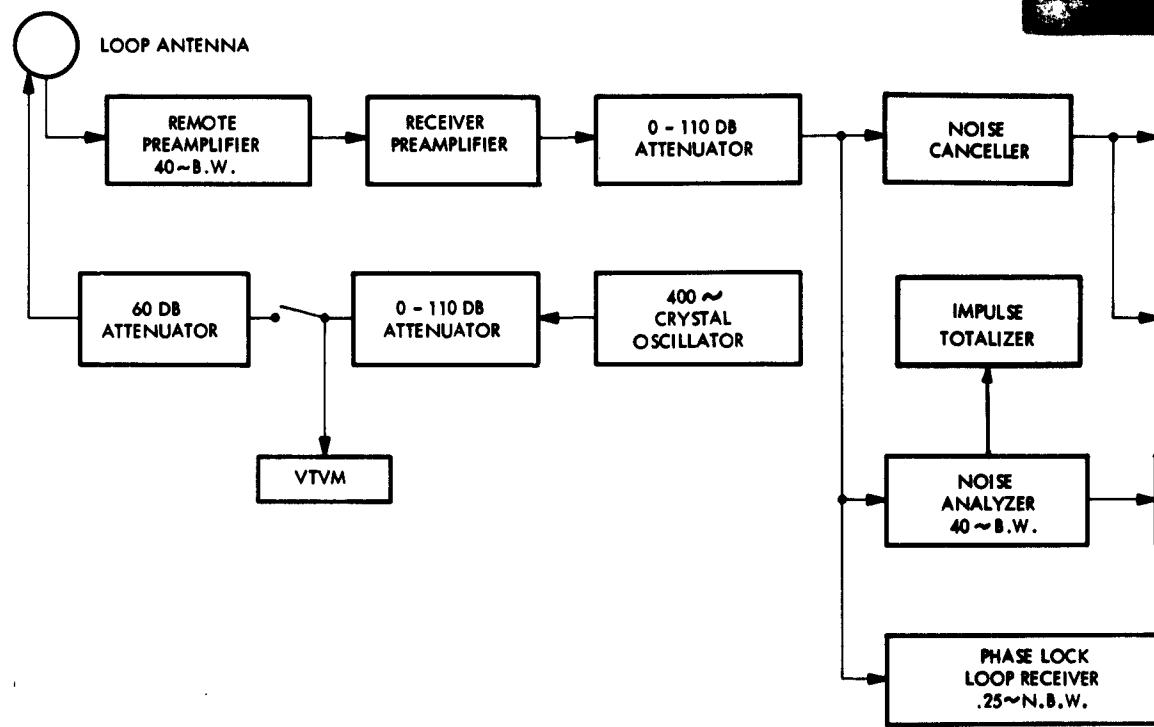


Figure 3. Receiver Facility Functional Block

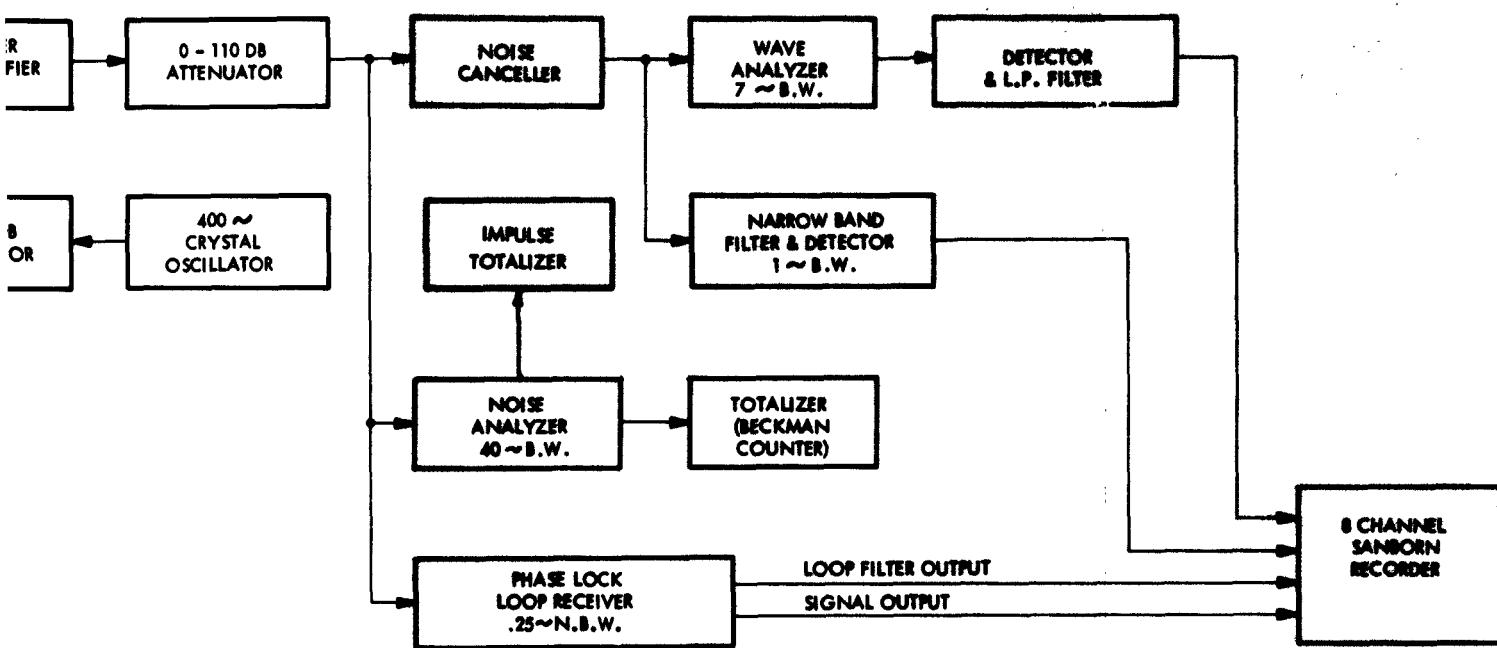


Figure 3. Receiver Facility Functional Block Diagram

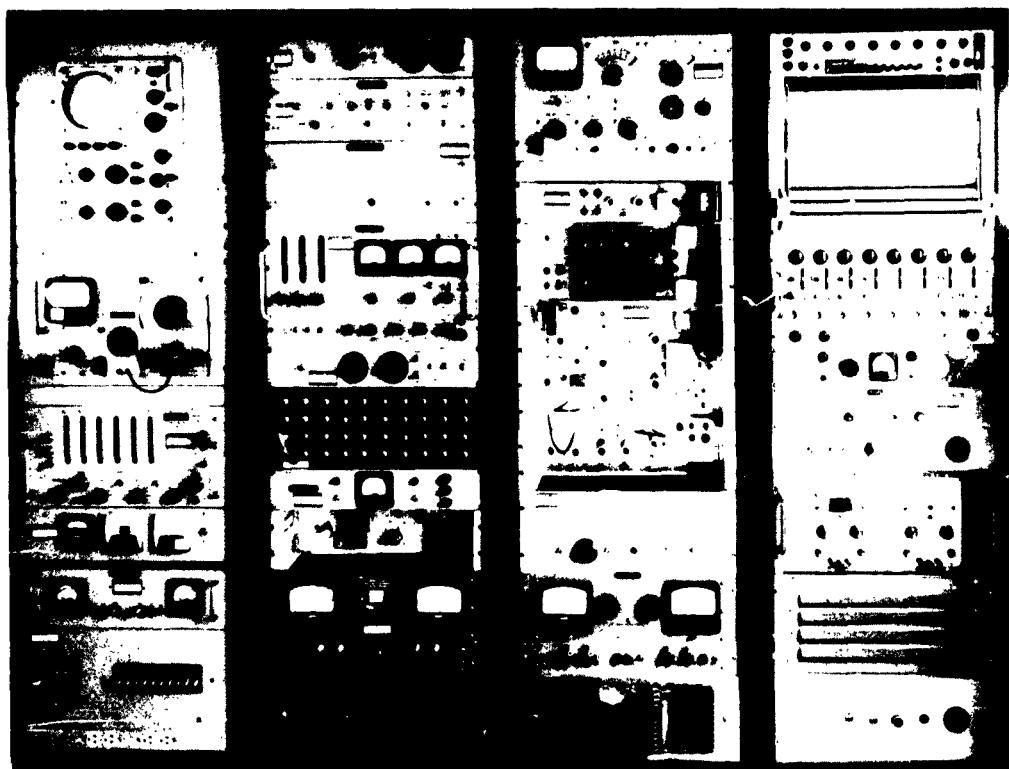


Figure 4. Receiver Trailer Interior

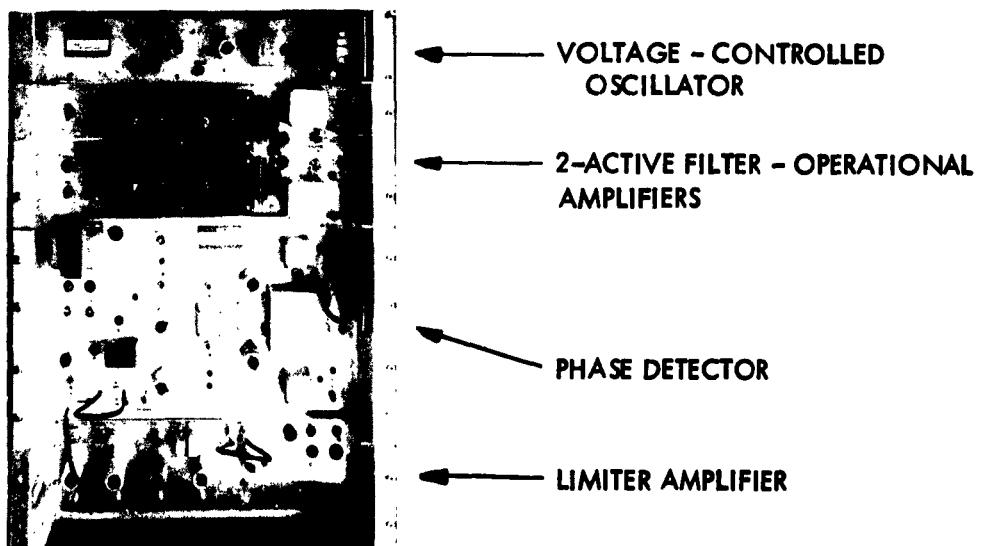


Figure 5. Phase-Lock Loop Detector System

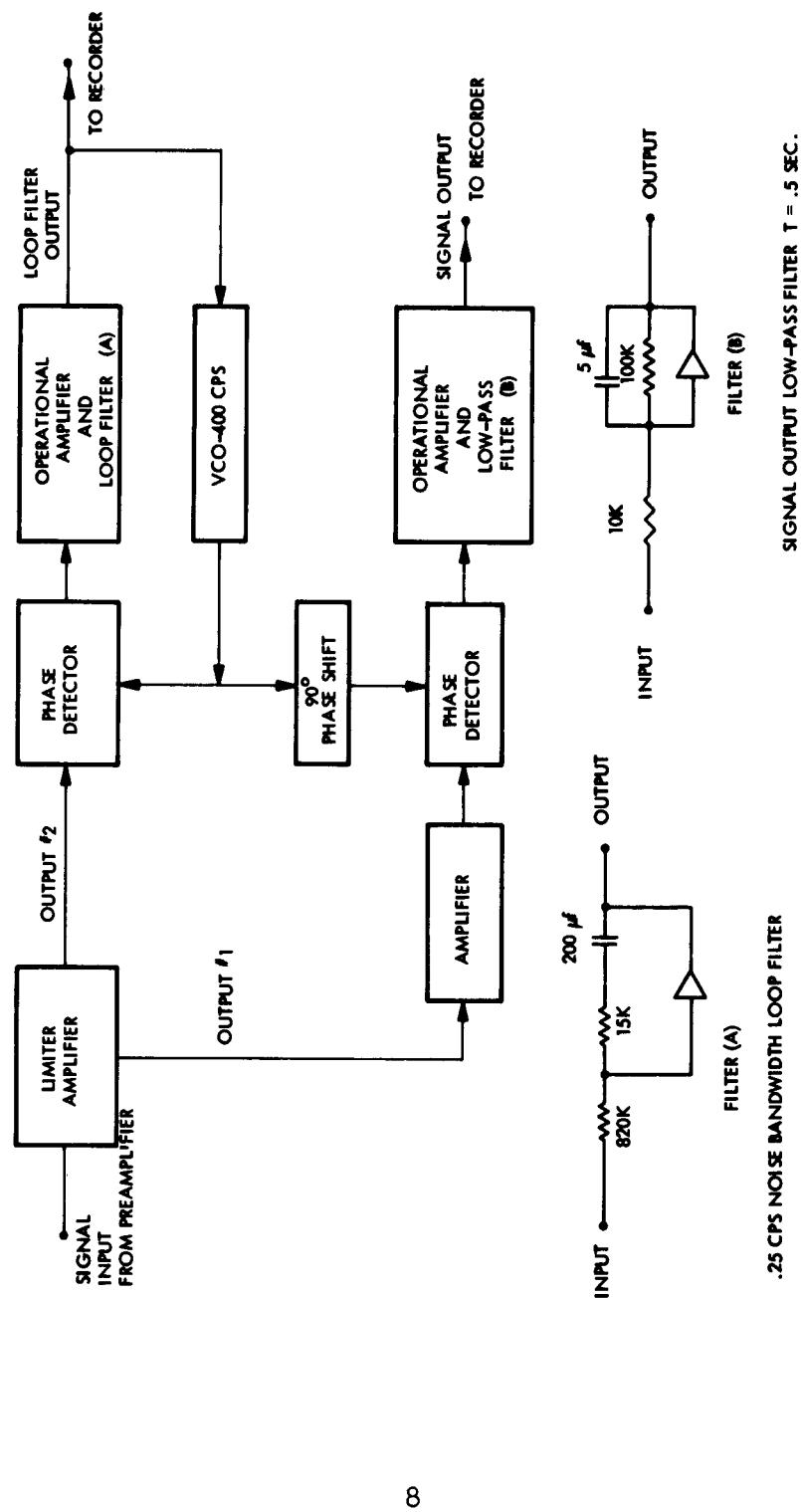


Figure 6. Phase-Lock Loop Detector System Block Diagram

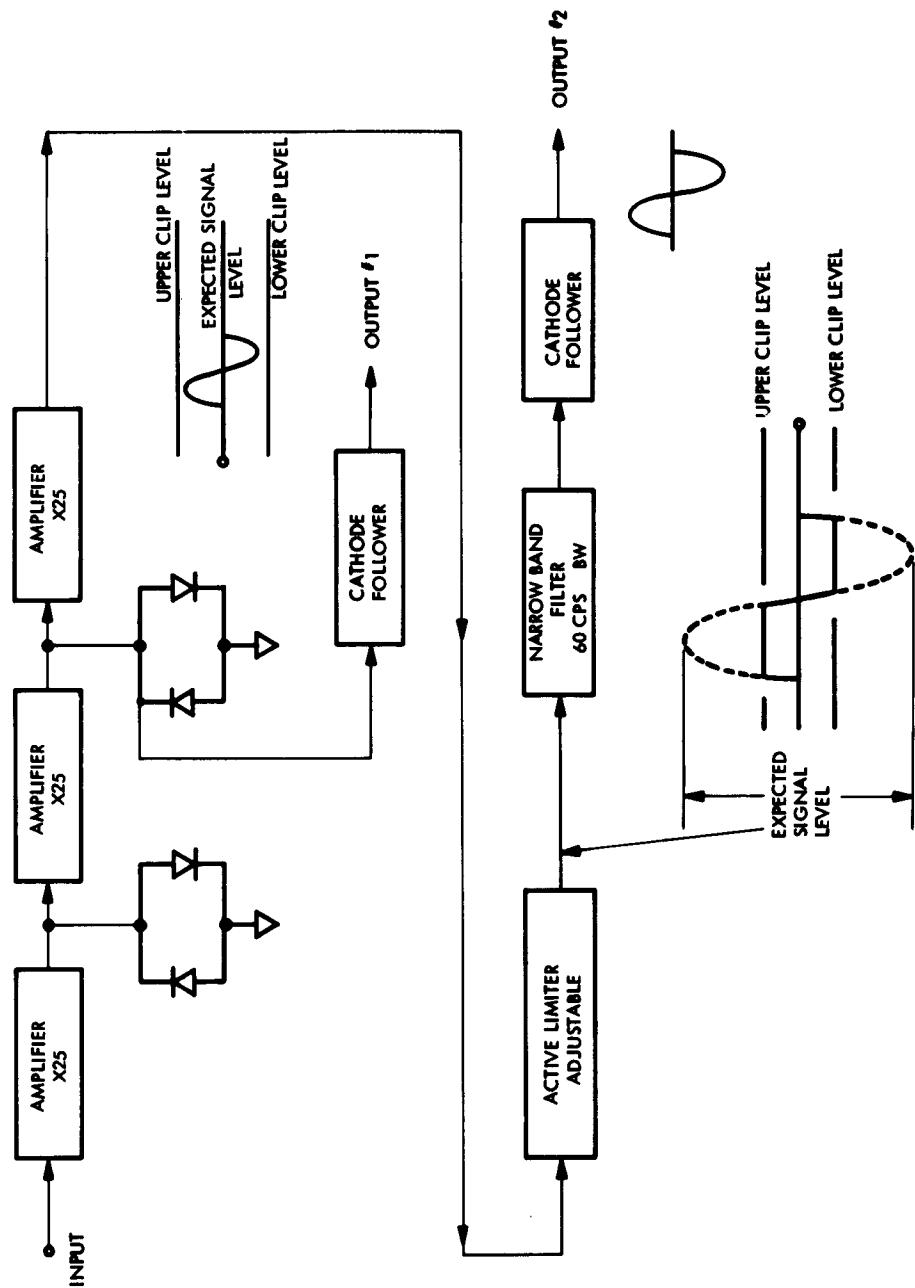


Figure 7. Phase-Lock Loop Detector Limiter Amplifier Block Diagram

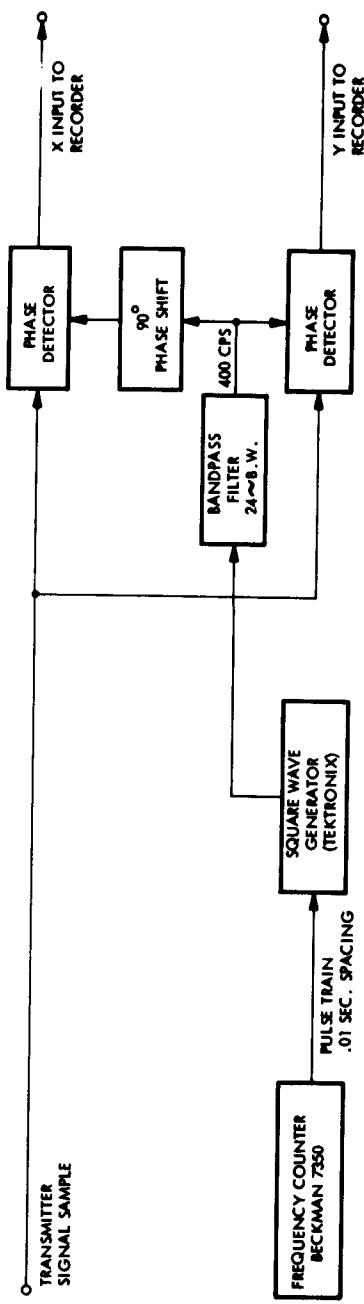


Figure 2. Transmitter Phase Measurement Functional Block Diagram

The output of the phase detector which is the product of a reference and signal input has maximum voltage output for sine wave reference and signal inputs in phase, and zero output for signals 90° out of phase. A phase difference between the reference and signal produces an output proportional to the cosine of the angle between the two signals.

A single phase detector output can show the phase difference between zero and 360 degrees, but cannot show the direction of rotation with respect to a reference signal. By simultaneously recording the outputs of two phase detectors, with a 90 -degree phase shift between inputs of one signal to each phase detector (see Figure 8), the two output signals will be 90 degrees apart, namely, one will be recorded as a cosine function, and the second as a sine function. By arbitrarily calling the cosine function "x" and the sine function "y", the two outputs make up the horizontal and vertical components of the relative phase angle. From this information, the phase angle and the direction of rotation can be determined by data reduction.

Attempts were made to record the phase angle on an x-y plotter, to obtain the phase angle directly. Due to atmospheric noise, transmitter phase instability, and the difficulty of recording time, it was decided to abandon this system in favor of using two channels of a Sanborn chart recorder. Using the chart recorder, the resulting data is averaged to reduce the effects of atmospheric noise. Figure 15 is an example of signal phase data received in the presence of atmospheric noise.

The noise analyzer¹ used at 400 cps is an adaption of the NBS circuit⁵ which measures the cumulative amplitude probability distribution of the noise envelope.

The atmospheric noise analyzer measures the percentage of time the noise level exceeds a preset threshold. A Schmitt trigger circuit is

adjusted to trip within 1 db of this threshold level. During the intervals that the threshold level is exceeded, the Schmitt trigger functions to open a gate that permits 10 kc clock pulses to be totalized over 10 or 100 second periods. By varying the gain of the amplifier with a calibrated attenuator, the threshold atmospheric noise level of the trigger circuit can be varied.

Additional circuitry was added to the Schmitt trigger to count the number of times the trigger cycles in a 10 or 100 second period. This corresponds to the total number of atmospheric noise impulses that exceed a predetermined atmospheric noise threshold level.

3.0 MEASUREMENT SCHEDULE AND PROCEDURE

Figure 9 shows the location of the transmitter near Boron, California, and the receiver 20 miles south of Carlsbad, New Mexico; a distance of 1300 km from the transmitter. This receiver location, on a 24,000 acre private cattle ranch, was at least five miles from all power lines, telephone lines, pipe lines, and public roads. At this location, man-made interference was not detectable in the receiver.

Transmission tests were conducted during the months of July and October, 1962. These tests were initiated in July with four test periods as shown in the Data Collection Schedule - July 1962 (Figure 10). The first two of these tests took place in July 17 and 18, and consisted of eight-minute transmissions on the half-hour from 0300 to 0600 hrs. MST. Two additional tests were conducted on July 24, from 0030 to 0600 hrs. MST, and on July 26, from 0030 to 0300 hrs. MST. These latter tests were an attempt to measure the propagation anomalies generated by a high altitude nuclear detonation. Failure of the launch vehicle at Johnston Island prevented the completion of this task.

Additional transmission tests were conducted for five days from October 24, to 28, 1962 inclusive from 0500 to 0810 hrs. MST, as shown in the data collection schedule October 1962 (Figure 11). These tests were for ten minutes every half-hour, except for two one-hour tests on October 27 and 28. These one-hour tests were conducted to determine the diurnal change in phase between the transmitter and receiver.

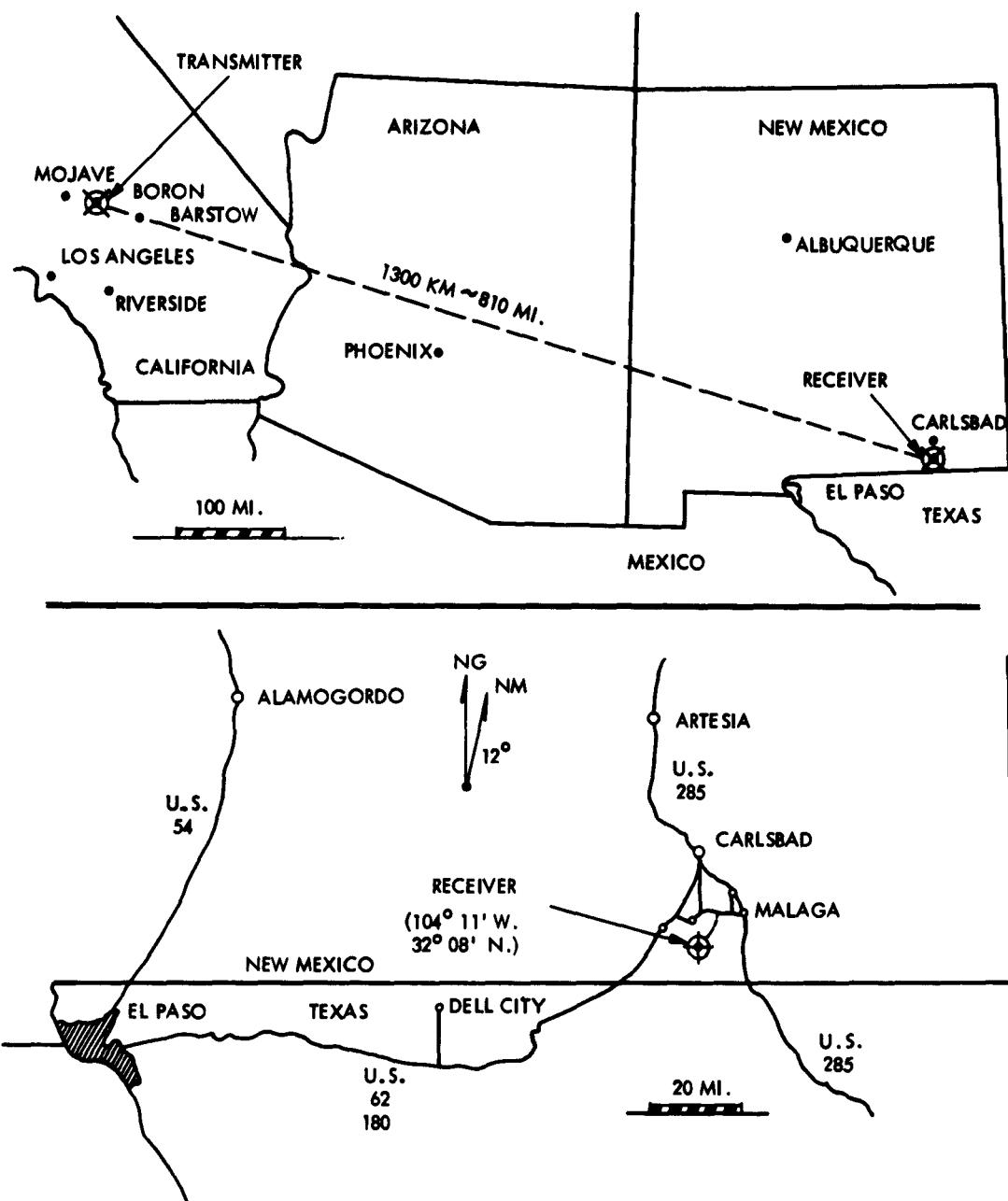


Figure 9. Relative Location of Transmitter and Receiver Sites

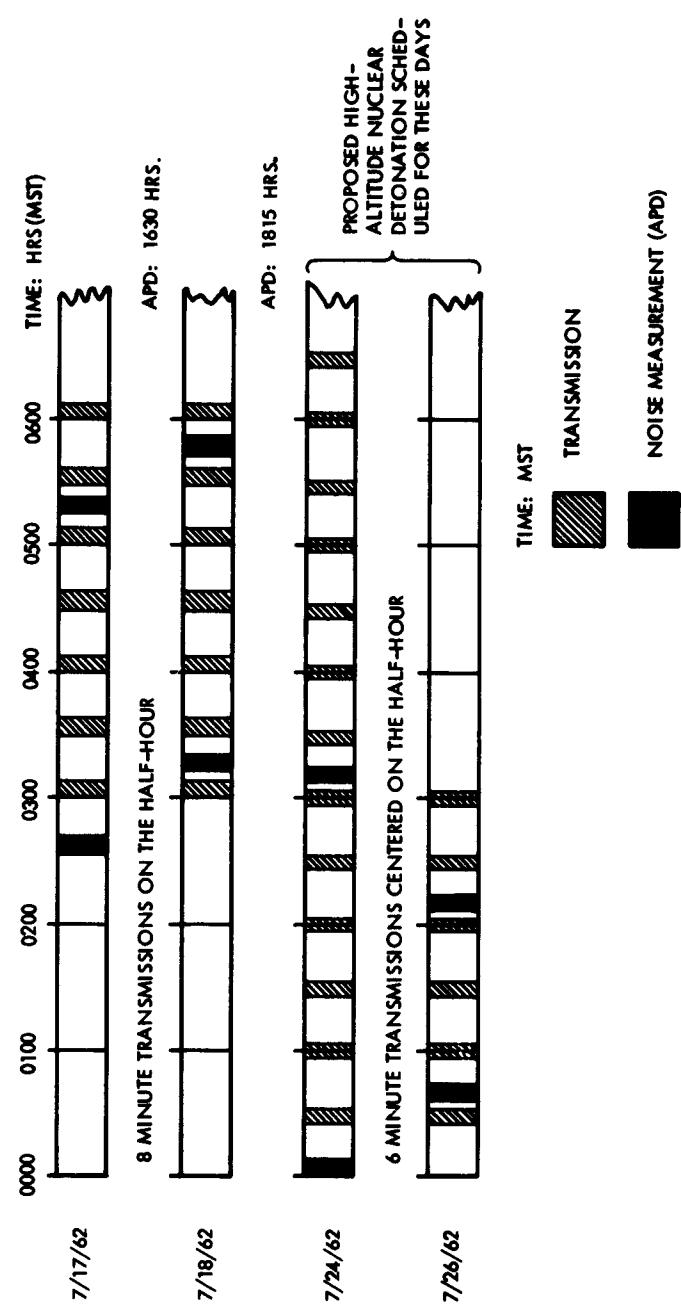


Figure 10. Data Collection Schedule - July 1962

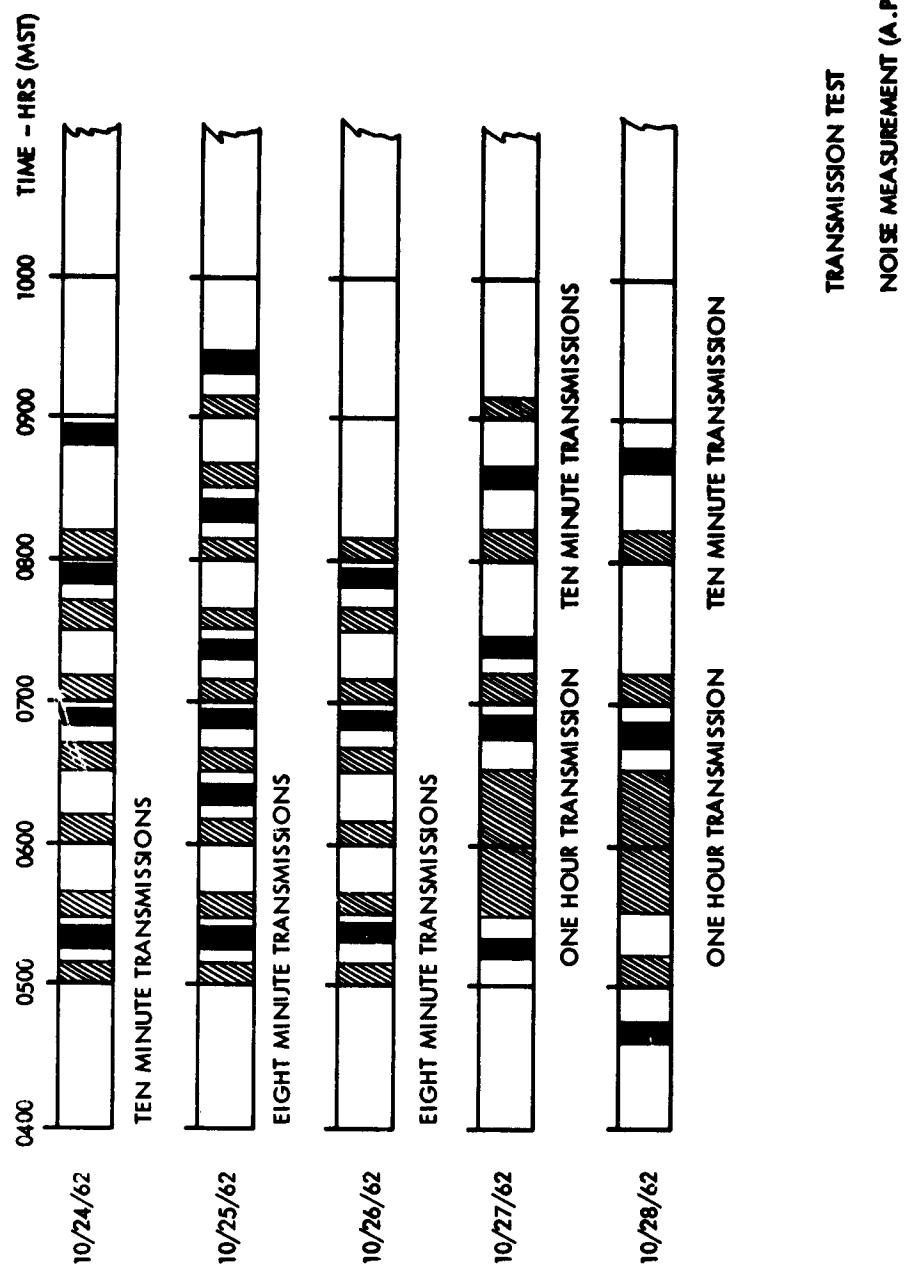


Figure 11. Data Collection Schedule - October 1962

Antenna current at the transmitter was maintained at 325 amperes, with a resulting effective dipole moment of 10^6 ampere-meters, as in previous tests¹. To prevent overheating the transmitter, antenna current was reduced to 250 amperes (-2.4 db relative to 325 amperes), for the first-half of each one-hour test, then increased to 325 amperes for the remaining 30 minutes.

Vertical electric field strength (E'_z) was detected in 7 cycle, 1 cycle, and .25 cycle (phase-lock loop) bandwidths and recorded on a chart recorder at the receiver as discussed in section 2.2, and shown in Figures 12 and 13. The tabulation of received field strengths is shown in Table 1 and 2.

The signal phase at both the transmitter and receiver was measured relative to 400 cycle reference oscillators using dual phase detectors as discussed in section 2.2. The resulting data was recorded in "x" and "y" components of the relative phase angle, (Figures 14 and 15).

A number of atmospheric noise amplitude probability distributions were recorded during both test periods. Simultaneously, atmospheric noise impulse data was recorded.

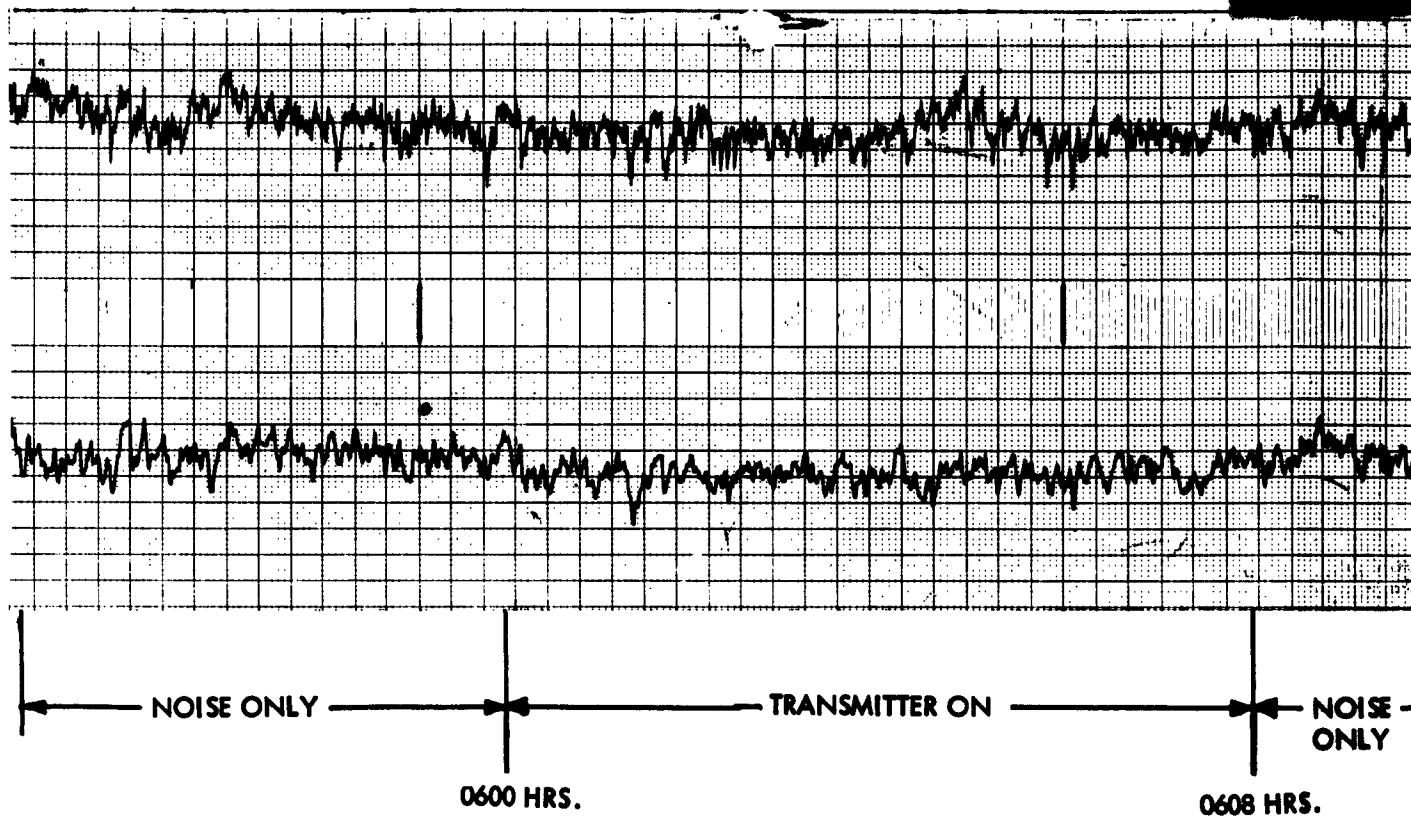


CHART SPEED: .25 MM/SEC.

INCREASING SIGNAL: DOWNWARD

OUTPUT FILTER: \approx 2 SEC.

REFERENCE: 0 DB = 100 μ V/M

SIGNAL LEVEL: \approx -38 DB

NOISE LEVEL: \approx -40 DB

TIME: MST

Figure 12. Sample Received Signal Strength

1

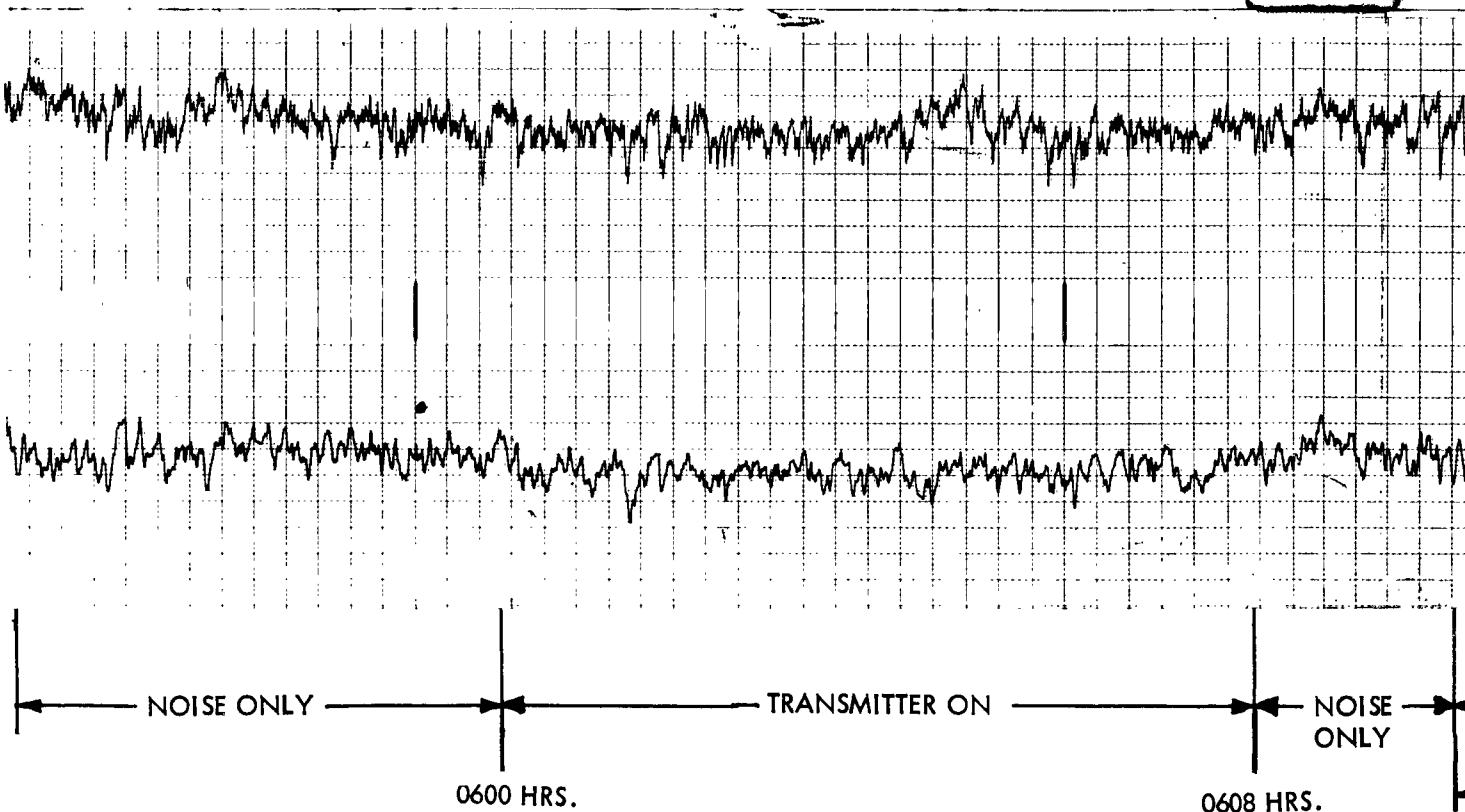


CHART SPEED: .25 MM/SEC.

INCREASING SIGNAL: DOWNWARD

OUTPUT FILTER: \approx 2 SEC.

REFERENCE: 0 DB = 100 μ V/M

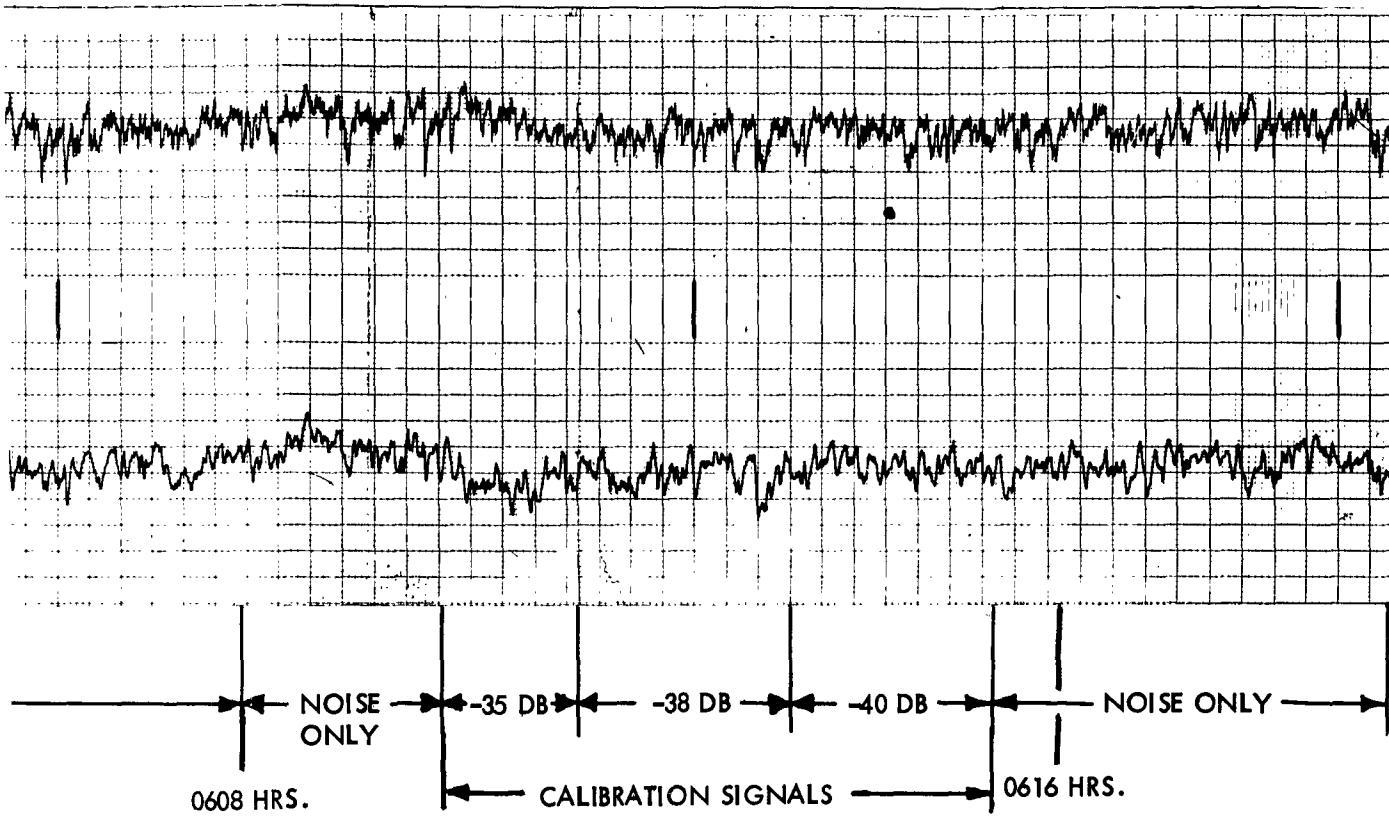
SIGNAL LEVEL: \approx -38 DB

NOISE LEVEL: \approx -40 DB

TIME: MST

Figure 12. Sample Received Signal Strength R

2



BW = 7 CPS

BW = 1 CPS

Sample Received Signal Strength Record - July 18, 1962

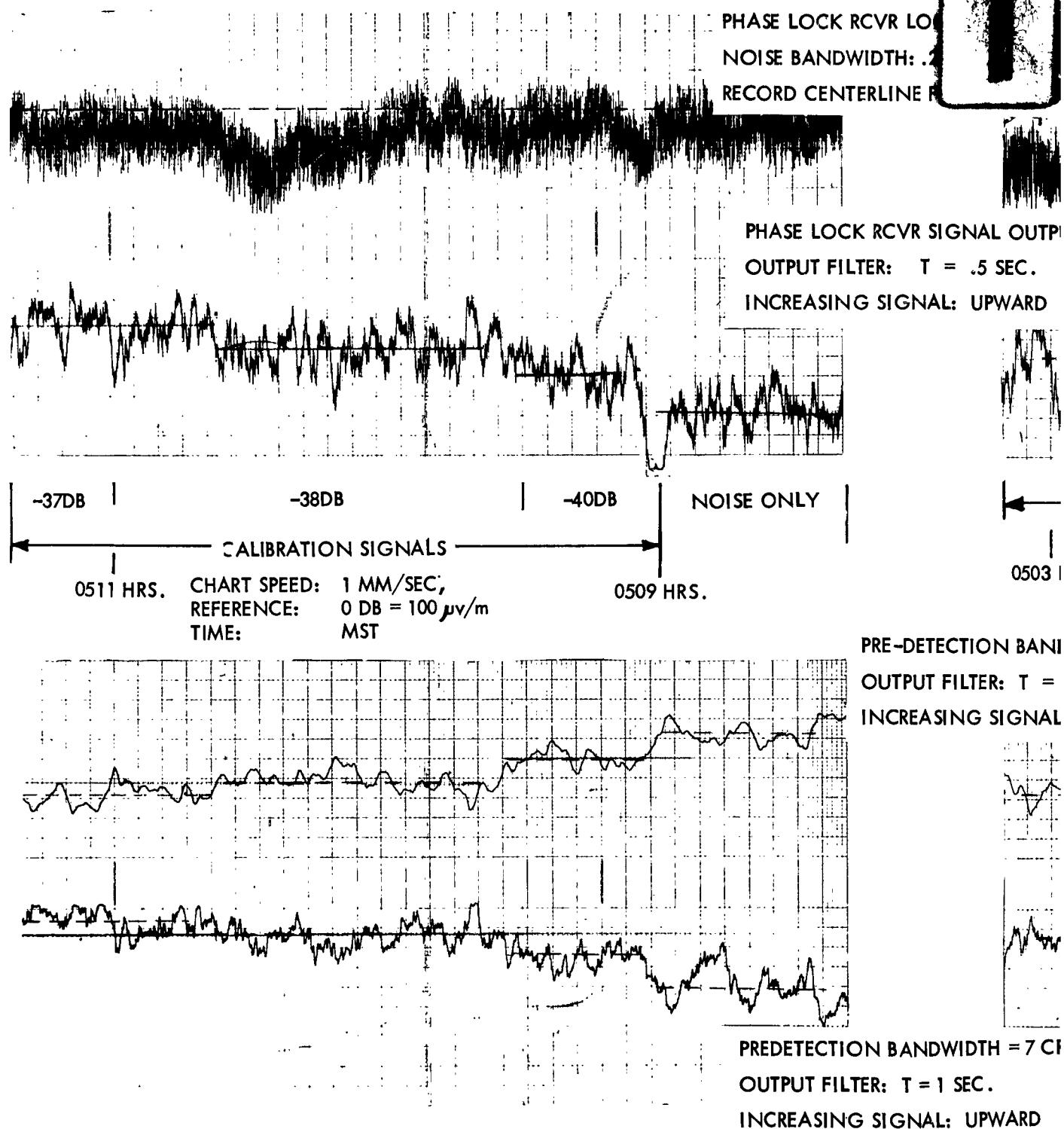


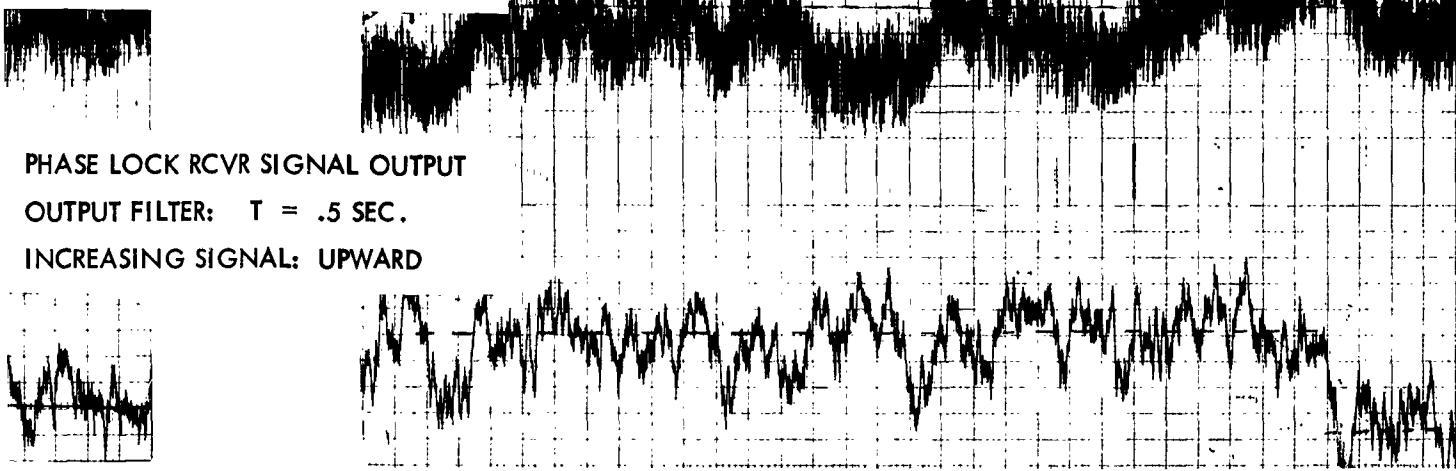
Figure 13. Sample Received Signal Strength Record

2

PHASE LOCK RCVR LOOP FILTER OUTPUT

NOISE BANDWIDTH: .25 CPS

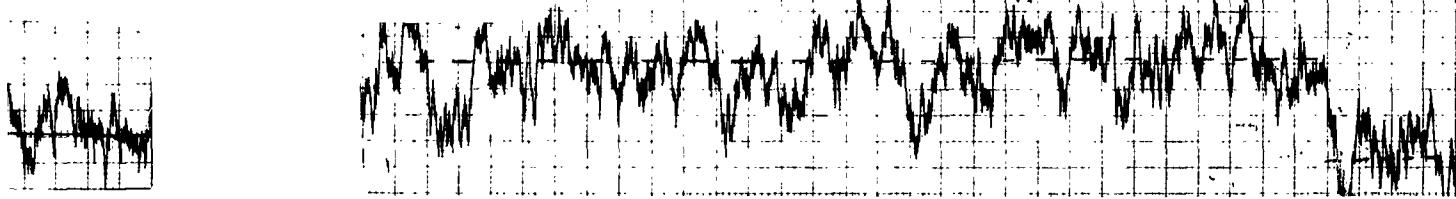
RECORD CENTERLINE FOR ZERO OUTPUT



PHASE LOCK RCVR SIGNAL OUTPUT

OUTPUT FILTER: $T = .5$ SEC.

INCREASING SIGNAL: UPWARD



SE ONLY

←———— TRANSMITTER ON —————→
(First Three Minutes of Eight Minute Transmission)

0503 HRS.

0502 HRS.

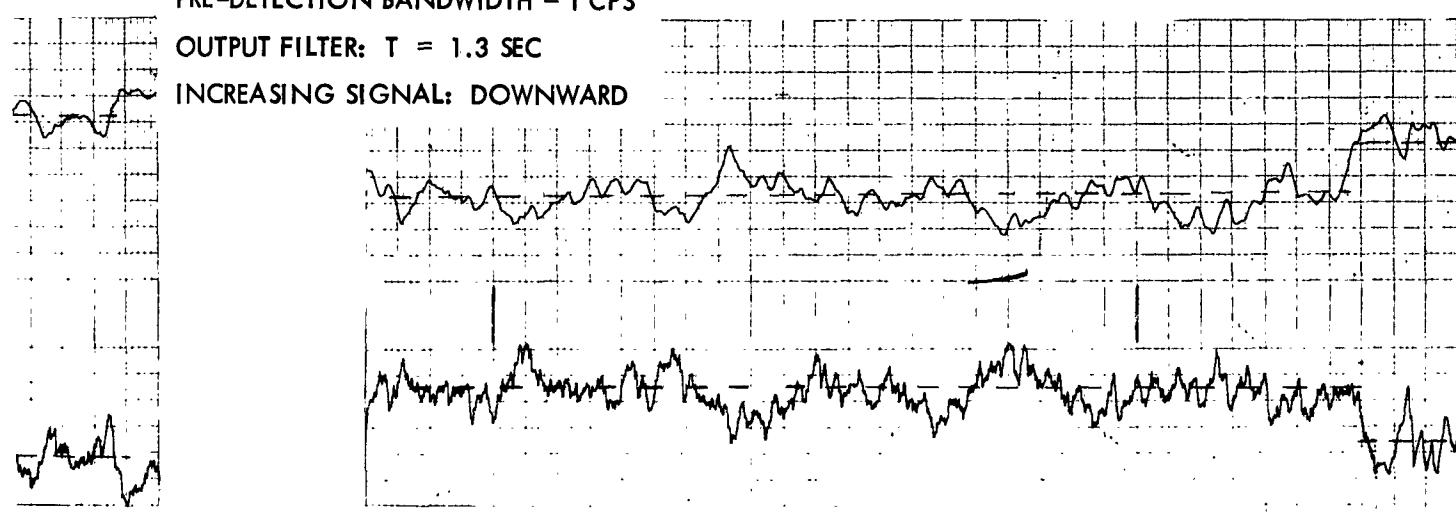
0501 HRS.

NOISE
ONLY

PRE-DETECTION BANDWIDTH = 1 CPS

OUTPUT FILTER: $T = 1.3$ SEC

INCREASING SIGNAL: DOWNWARD



PREDTECTION BANDWIDTH = 7 CPS

OUTPUT FILTER: $T = 1$ SEC.

INCREASING SIGNAL: UPWARD

Received Signal Strength Record - October 25, 1962

TABLE 1. TRANSMISSION TESTS - JULY 1962
BORON, CALIFORNIA TO CARLSBAD, N.M.

$\rho = 1300$ km

DATE	TIME HOURS(MTS)	EQUIVALENT VERTICAL ELECT. F.S. DB REL. 100 μ v/m	ESTIMATED THRESHOLD SIGNAL LEVEL DB REL.100 μ v/m	CARLSBAD, N.M. GROUND SUNRISE (HRS. - MST)
7/17/62	0300 0330 0400 0430 0500 0530 0600	Not Detectable Not Detectable -37 to -40 -38 to -42 -40 -41 -41	-30 -35 -42 -42 -44 -42 -45	0502
7/18/62	0300 0330 0400 0430 0500 0530 0600	Not Detectable -40 Not Detectable -40 -38 to -40 -40 to -42 -38	-30 -40 -35 -40 -40 -42 -40	0503
7/24/62 to 7/26/62		Attempted detection of nuclear blast. Local thunderstorm activity; did not detect Boron transmissions.		

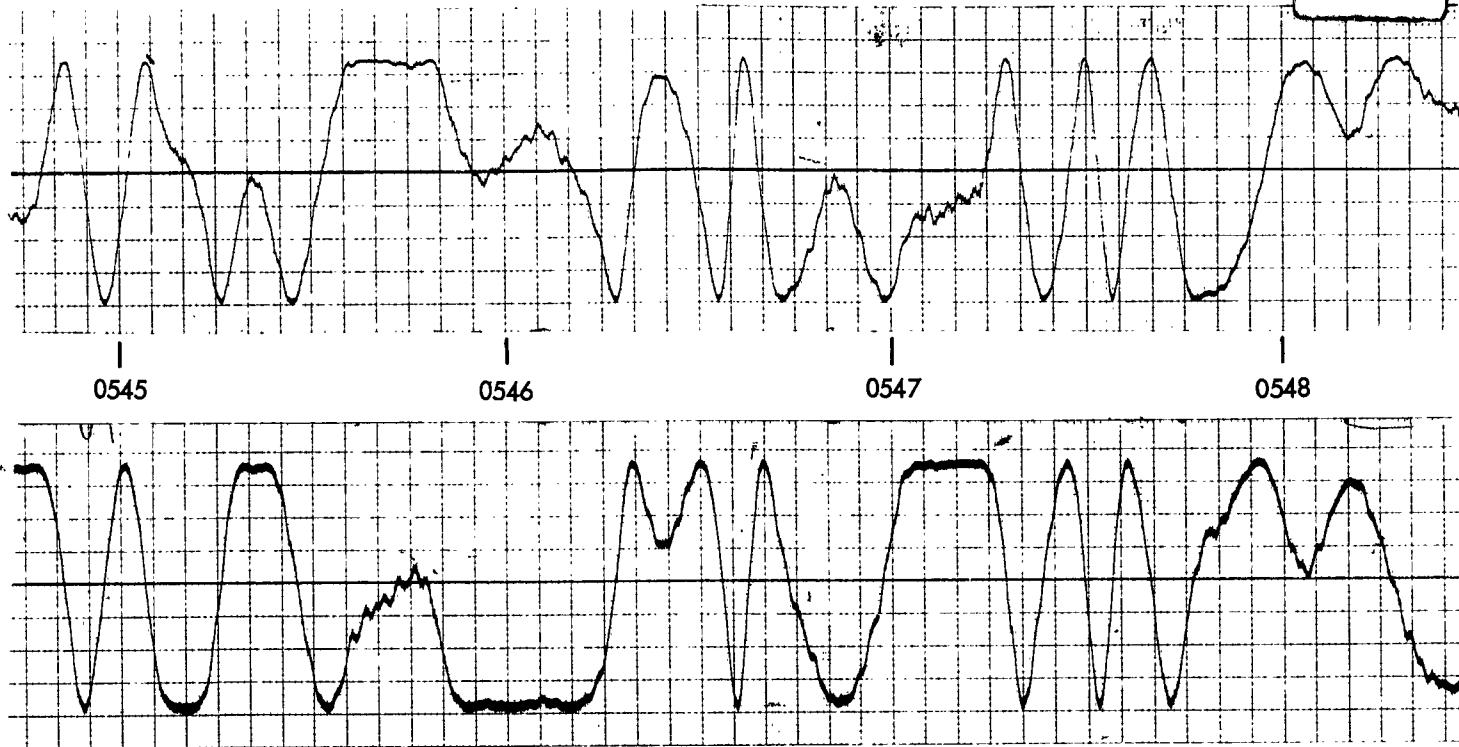
TABLE 2. TRANSMISSION TESTS - OCTOBER 1962
BORON, CALIFORNIA TO CARLSBAD, N. M.

$\rho = 1300$ km

DATE	TIME HOURS(MTS)	EQUIVALENT VERTICAL ELECT. F. S. DB REL. 100 μ v/m	ESTIMATED THRESHOLD SIGNAL LEVEL DB REL.100 μ v/m	CARLSBAD, N. M. GROUND SUNRISE (hrs. - MST)
10/24/62	0530 0600 0630 0700 0730 0800	-40 ± 1db -43 ± 1db -43 ± 2db -45 ± 2db Not detectable Not detectable	-44 -46 -45 -48 -47 -47	0607
10/25/62	0500 0530 0600 0630 0700 0730 0800 0830 0900	-38 ± 1db -43 ± 1db -41 ± 1db -45 ± 1db -45 ± 1db -46 ± 1db Not detectable Not detectable Not detectable	-45 -47 -48 -48 to 50 -49 -49 -46 -40 -40	0608
10/26/62	0500 0530 0600 0630 0700 0730 0800	-40 ± 2db -42 ± 1 -40 to -43 Not detectable Not detectable Not detectable Not detectable	-46 -44 -44 -45 -43 -43 -43	0609
10/27/62	0530 to 0630 0700 0800	-38 ± 2 -46 ± .5db -45 ± 2db Not detectable	-50 -50 -50 -40	0609
10/28/62	0500 0530 to 0630 0700 0800	-38 ± 1db -38 ± 2db* Not detectable Not detectable Not detectable	-46 -44 -43 -43 -42	0610

* Field Strengths have been corrected to the equivalent field strength of the transmitter when operated at full power.

1

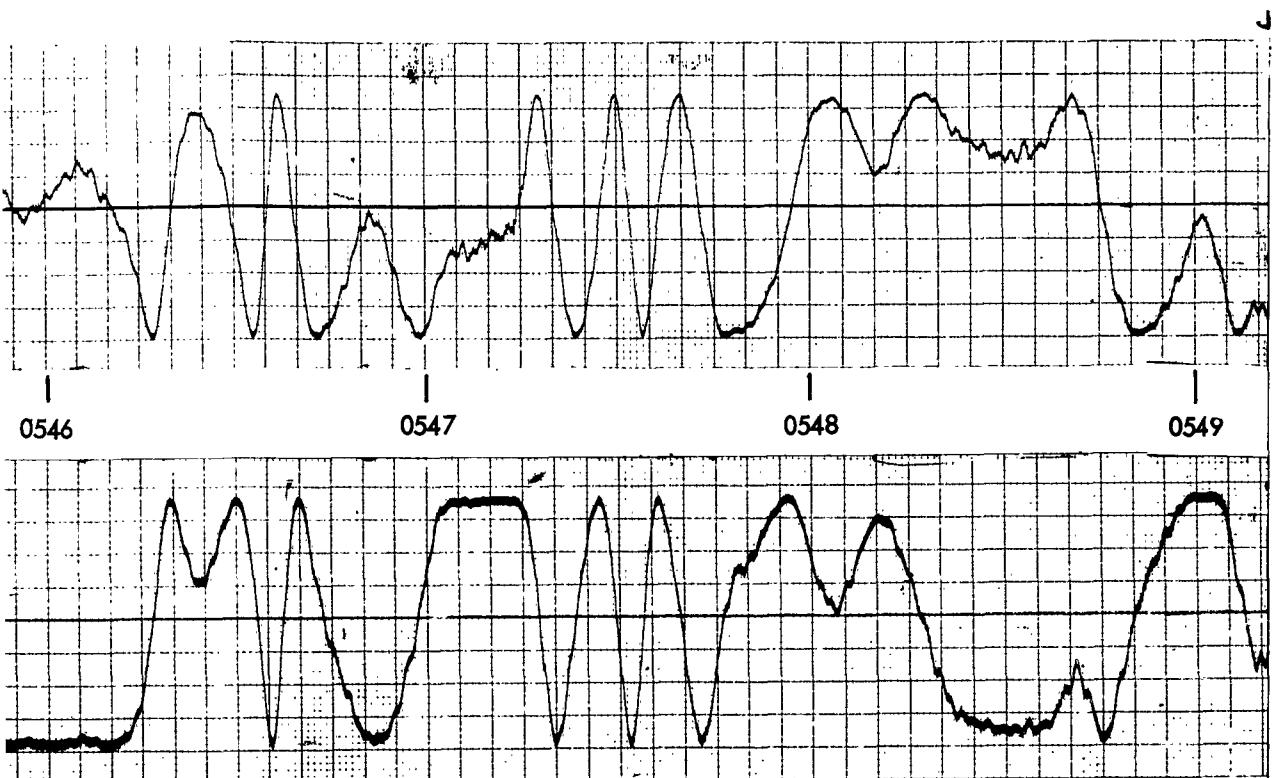


TIME: 0545 HRS. TO 0549 HRS. PDT (MST)

RECORD SPEED: 1 MM/SEC.

LOCATION: BORON, CALIFORNIA

Figure 14. Sample Transmitted Phase Record - October 27, 1962

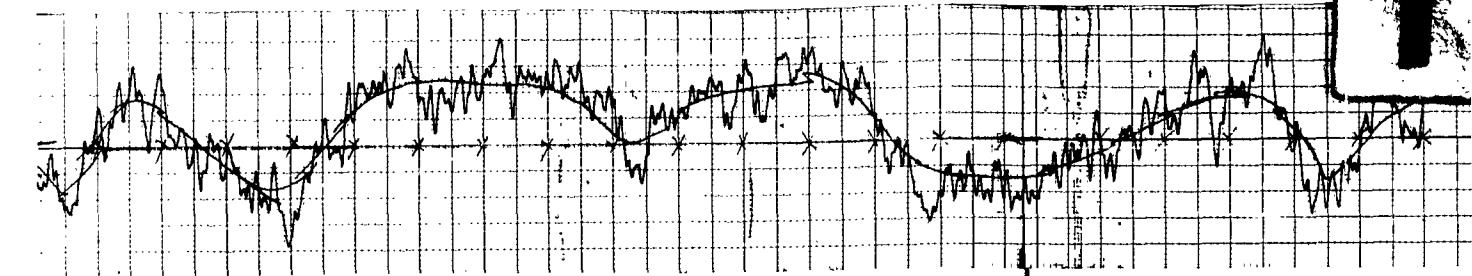


TIME: 0545 HRS. TO 0549 HRS. PDT (MST)

RECORD SPEED: 1 MM/SEC.

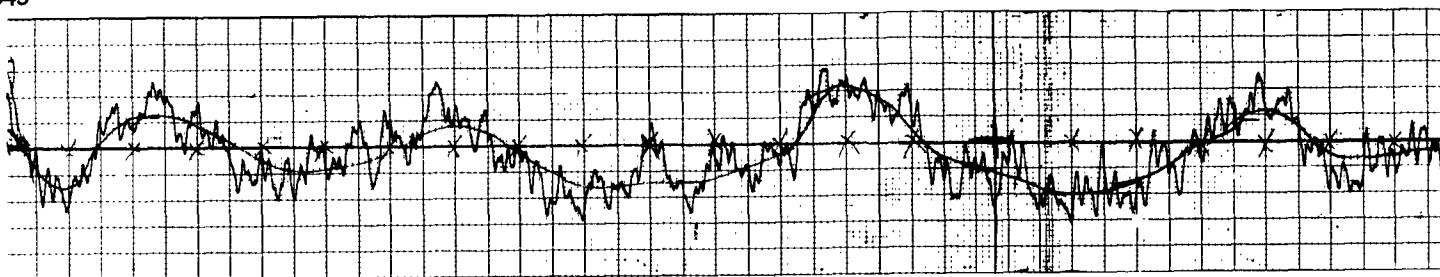
LOCATION: BORON, CALIFORNIA

Figure 14. Sample Transmitted Phase Record - October 27, 1962



0545

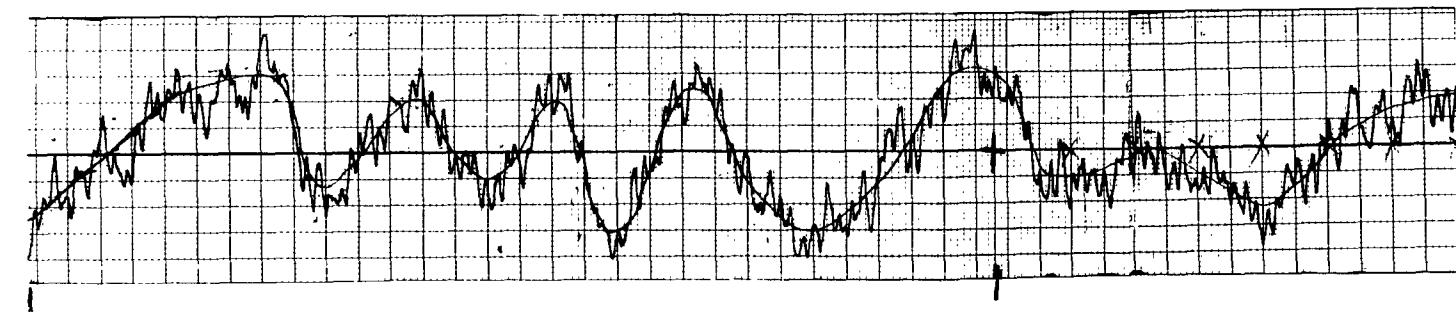
0546



TIME: 0545 HRS. - 0549 HRS. MST

RECORD SPEED: 2.5 MM/SEC.

LOCATION: CARLSBAD, N.M.



0547

0548

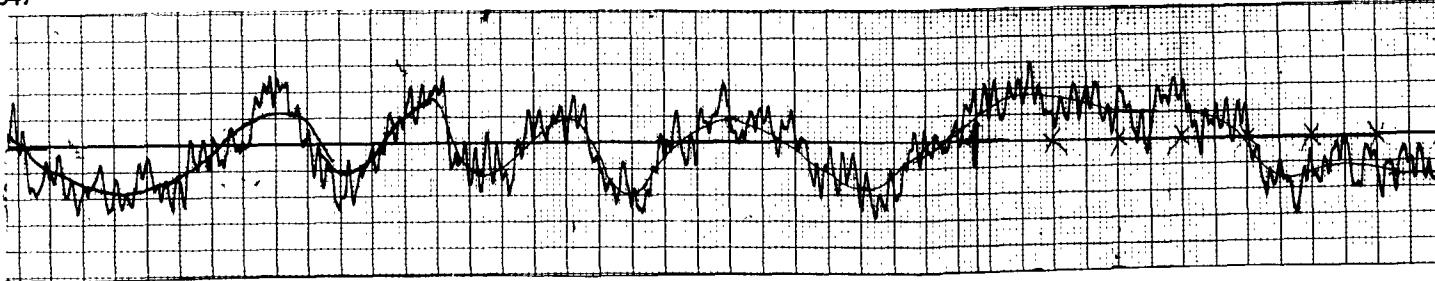
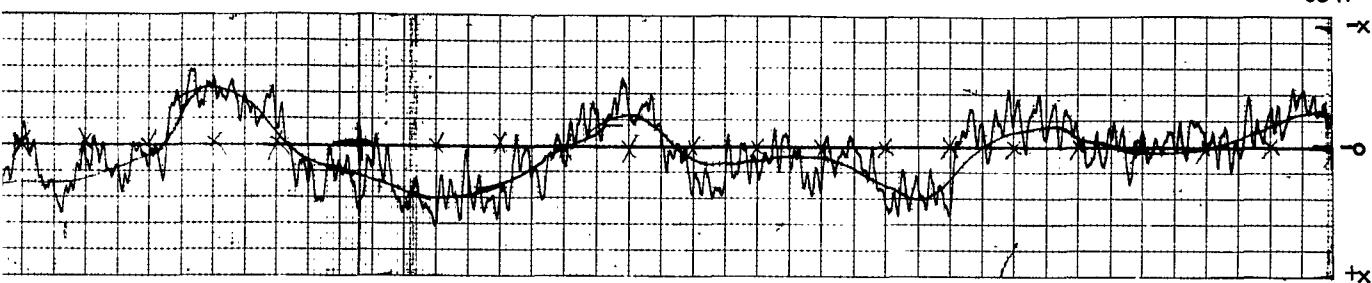
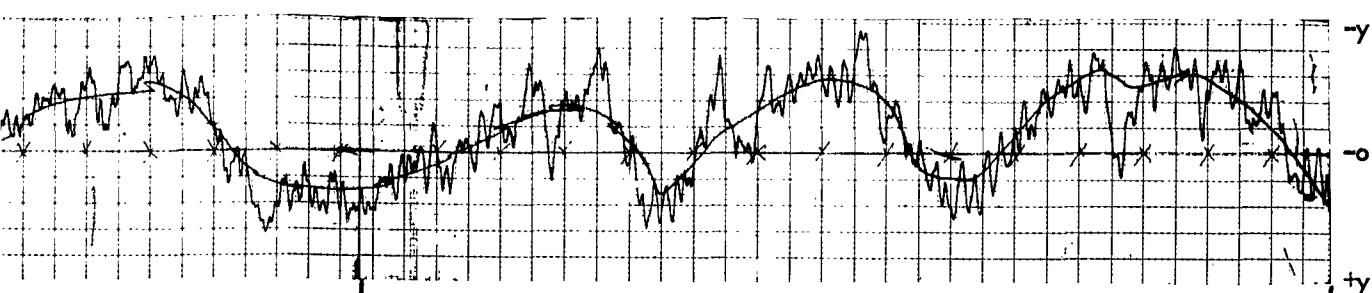


Figure 15. Sample Received Phase Record - October 27, 1962

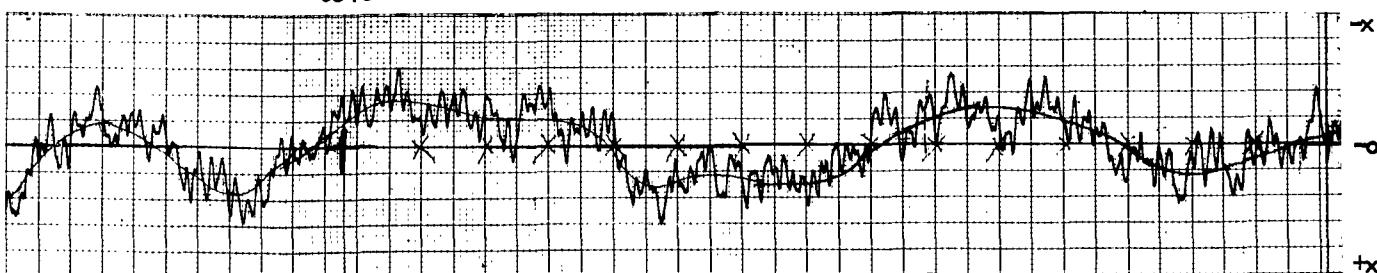
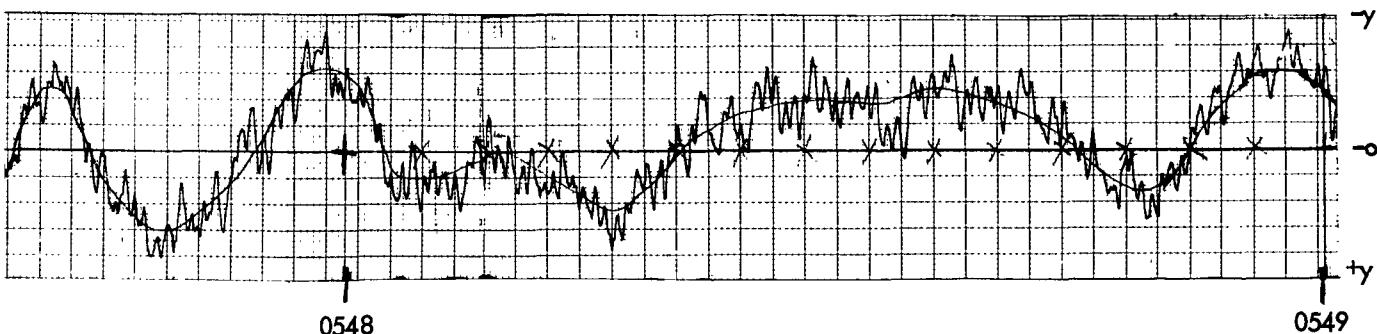
2



TIME: 0545 HRS. - 0549 HRS. MST

RECORD SPEED: 2.5 MM/SEC.

LOCATION: CARLSBAD, N.M.



15. Sample Received Phase Record - October 27, 1962

4.0 ANALYSIS OF EXPERIMENTAL RESULTS4.1 Signal Strength

The receiver was located at a distance of 1300 km from the transmitter at the site described in Section 3.0. Examination of Figure 17 shows that this is the minimum range for observation of diurnal propagation effects.

Except during the phase measurement tests of October 27 and 28, 1962, described in Section 3.0, the antenna current was maintained at 325 amperes. Field strengths tabulated in Tables 1 and 2 have been normalized to the equivalent field strength for an antenna current of 325 amperes (300 kw transmitter power output).

Figure 16 shows signal strength versus time relative to ground sunrise at the receiver. All detectable transmissions are shown for the month of July and October. Transmissions more than 1-1/2 hours before sunrise and 1 to 1-1/2 hours after sunrise were not detectable due to the low signal to atmospheric noise ratio.

Measurements of the diurnal variation taken in July were inconclusive. On July 17 (Figure 16), the signal attenuation increased approximately 3 db in 2 hours. On July 18 the signal strength was 2 db greater one hour after sunrise than the value recorded one hour before sunrise. Figure 12 shows the relative signal, noise and calibration levels recorded at that time. Atmospheric noise levels were high, as shown in Figure 20, and

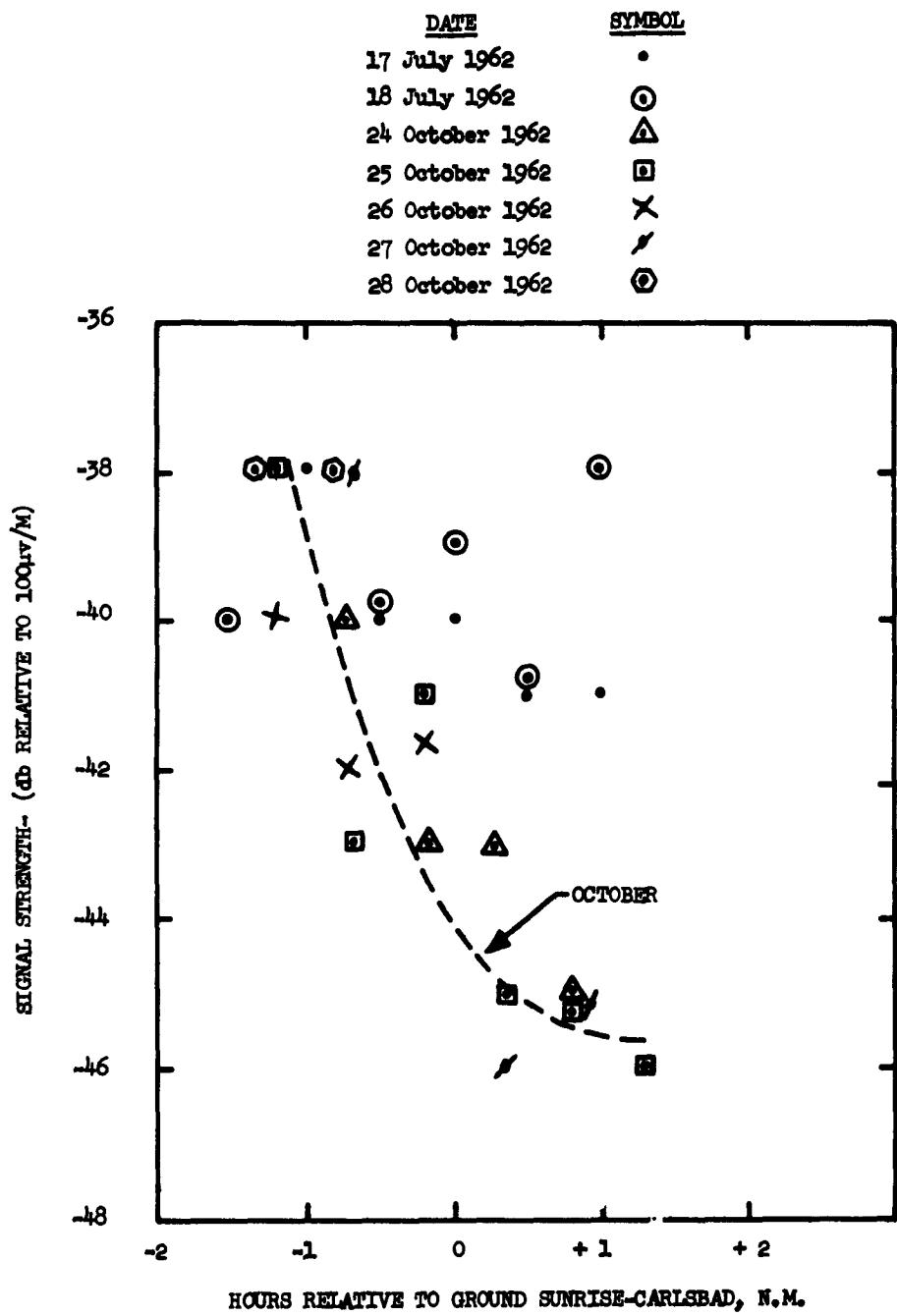


Figure 16. Signal Strength vs. Ground Sunrise - Carlsbad, New Mexico

discussed in Section 4.3, making signal detection difficult. Since the data points did not fall in a pattern they were not connected.

Data recorded in October for five succeeding days show consistent results as shown in Figure 16. All values of field strength fall within 1 to 2 db of the curve drawn as the estimated average value.

Transmissions received one hour before sunrise have signal strengths of approximately -38 to -40 db* while those received 1/2 hour or more after sunrise have signal strengths of -45 to -46 db.*

Referring to Figure 16, signal attenuation should increase rapidly as the ionosphere changes from a nighttime to daytime state. At the receiver, ionosphere sunrise will occur before ground sunrise causing signal level attenuation to increase before ground sunrise.

Figure 17 is the comparison of theoretical and experimental values of signal strength at various distances from the transmitter, based on a transmitter power output of 300 kw. The theoretical curves were computed¹ from theories developed by Wait³ and Galejs.⁴

Comparison of nighttime theoretical and October experimental results, at 1300 km, show that the experimental values are approximately 2 db less than predicted, while daytime levels are 4 db less. The 6 to 7 db change in level from night to day agrees within 1 to 2 db of the theoretical changes, but with an offset of several db. The results show that the signal may be attenuated more sharply than originally anticipated. Confirmation

* 0 db = 100 μ uv/M.

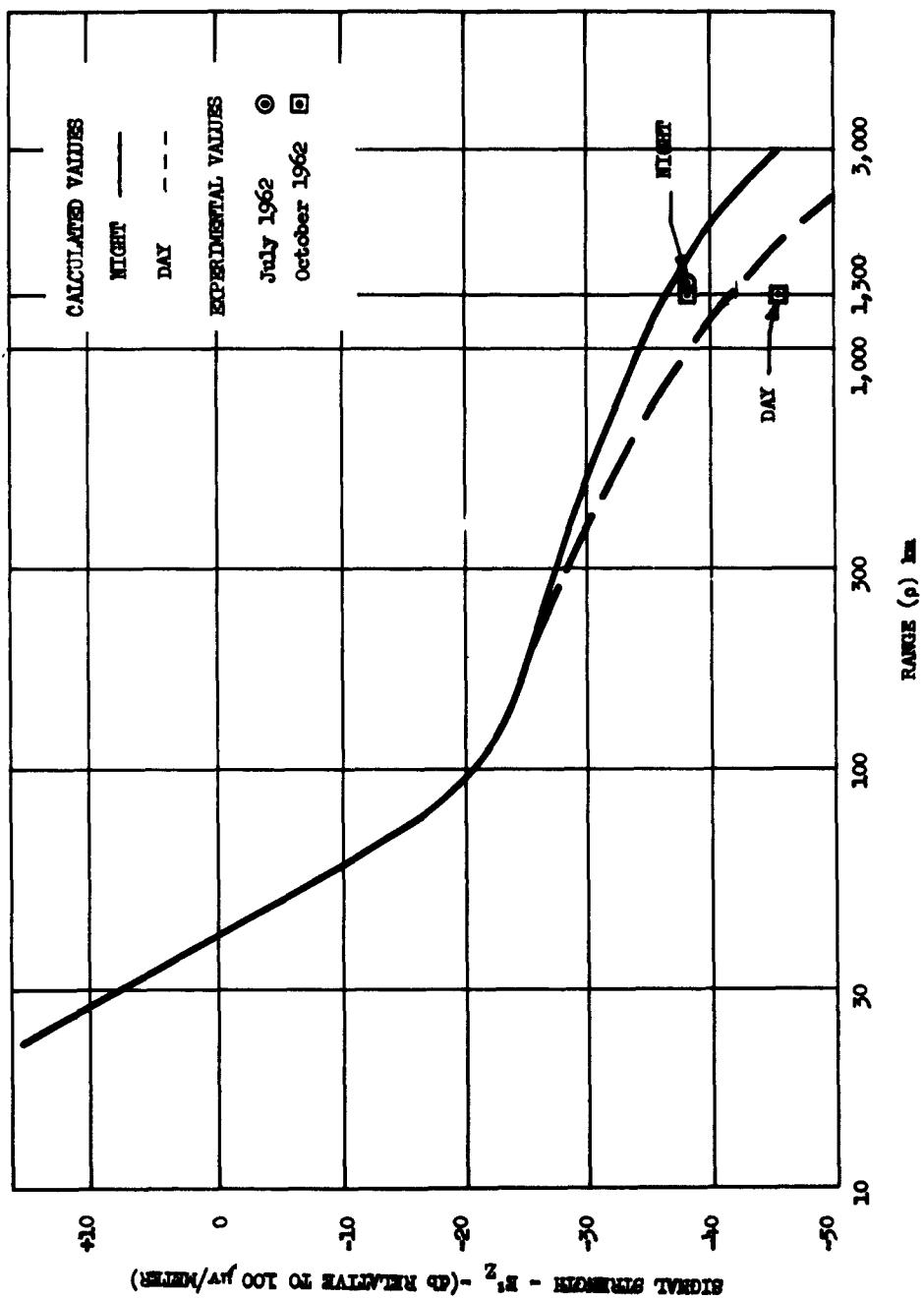


Figure 17. Theoretical and Measured Values of Signal Strength vs. Range

of this must await collection of additional data at greater distances from the transmitter and over longer periods of time.

4.2 Transmission Path Phase Measurements

Relative phase of the signal was recorded at both the transmitter and receiver with dual phase detectors and associated equipment as shown in Figures 2 and 8. One hour tests were conducted from 0530 to 0630 hours MST on October 27 and 28, 1962. The data from the first test has been reduced and analyzed. The phase data recorded on October 28 was not reduced as local storm activity caused high atmospheric noise as shown in Table 2, and Figure 27. The initial reduction of the data showed an offset between the two reference oscillators of 1.22 cps. Figure 18 is a graph of this reduced phase record with the 1.22 cps offset removed.

The results, shown in Figure 18, indicate a phase shift greater than 8π radians and seemingly indicate unstable transmission path characteristics prior to illumination of the ionosphere. Since the results are inconsistent, stability of the measurement equipment was suspected and the reference oscillators were checked for frequency drift. The 400 cps crystal oscillator used in the receiver was found to be temperature sensitive. Therefore, in light of temperature variations present in the receiver trailers, the results must be judged inconclusive. The record most likely represents a comparison of the relatively unstable receiver reference oscillator with the reference at the transmitter. The fact that such a record

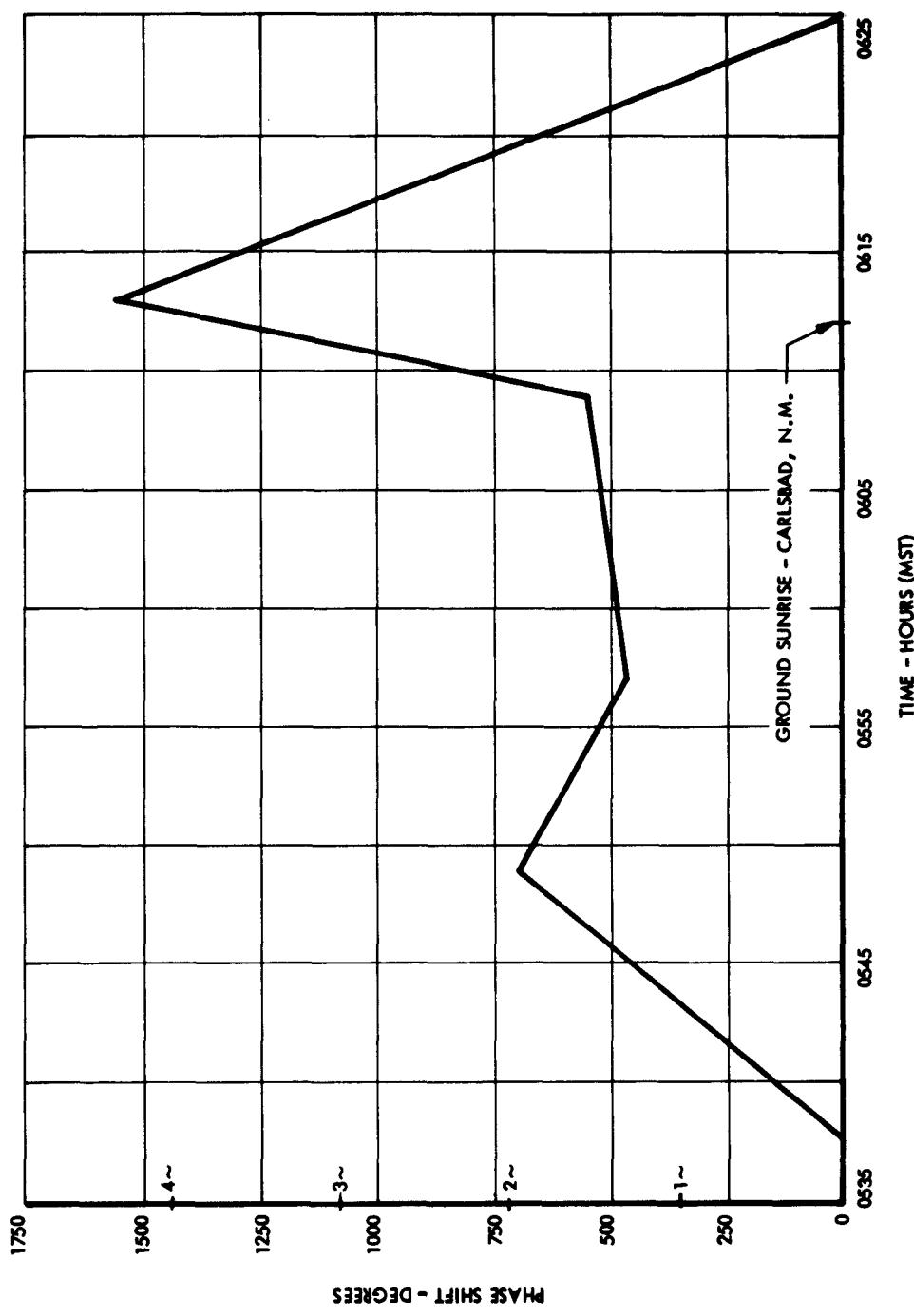


Figure 18. Transmission Path Phase Record - October 27, 1962

can be secured over a 1300 km path using a signal which is only slightly above the noise in a 1 cps band shows that a useful technique has been evolved.

4.3 Atmospheric Noise

During the two data collection periods, July and October, a number of atmospheric noise amplitude probability distributions were recorded as shown in Figures 19-21.

The second test period in October was chosen for a period of minimum storm activity. For 4 of the 5 days of testing, only 1 day of local thunderstorm activity was present; (October 28) as shown in Figures 22-26.

The highest noise in October was approximately the same level as the lowest in July for the same time in relation to sunrise. In October, the best receiving conditions were on mornings when the atmospheric noise had the least number of high level impulses, with the lower levels approximately equal to the receiver thermal noise in a 40 cps bandwidth. October 25 is an example of this with the recorded thermal noise distribution of the dummy loop as shown in Figure 22.

The majority of the noise data was recorded during the early morning hours. The low signal level limited data recording to times near sunrise when the received atmospheric noise was at a minimum. The high level atmospheric noise impulses are believed to originate, primarily, in

Location: Carlsbad, N.M.
 $f_0 = 400$ CPS
 $BW = 40$ CPS
A 0235 HRS., MST
B 0515 HRS., MST
C 1630 HRS., MST

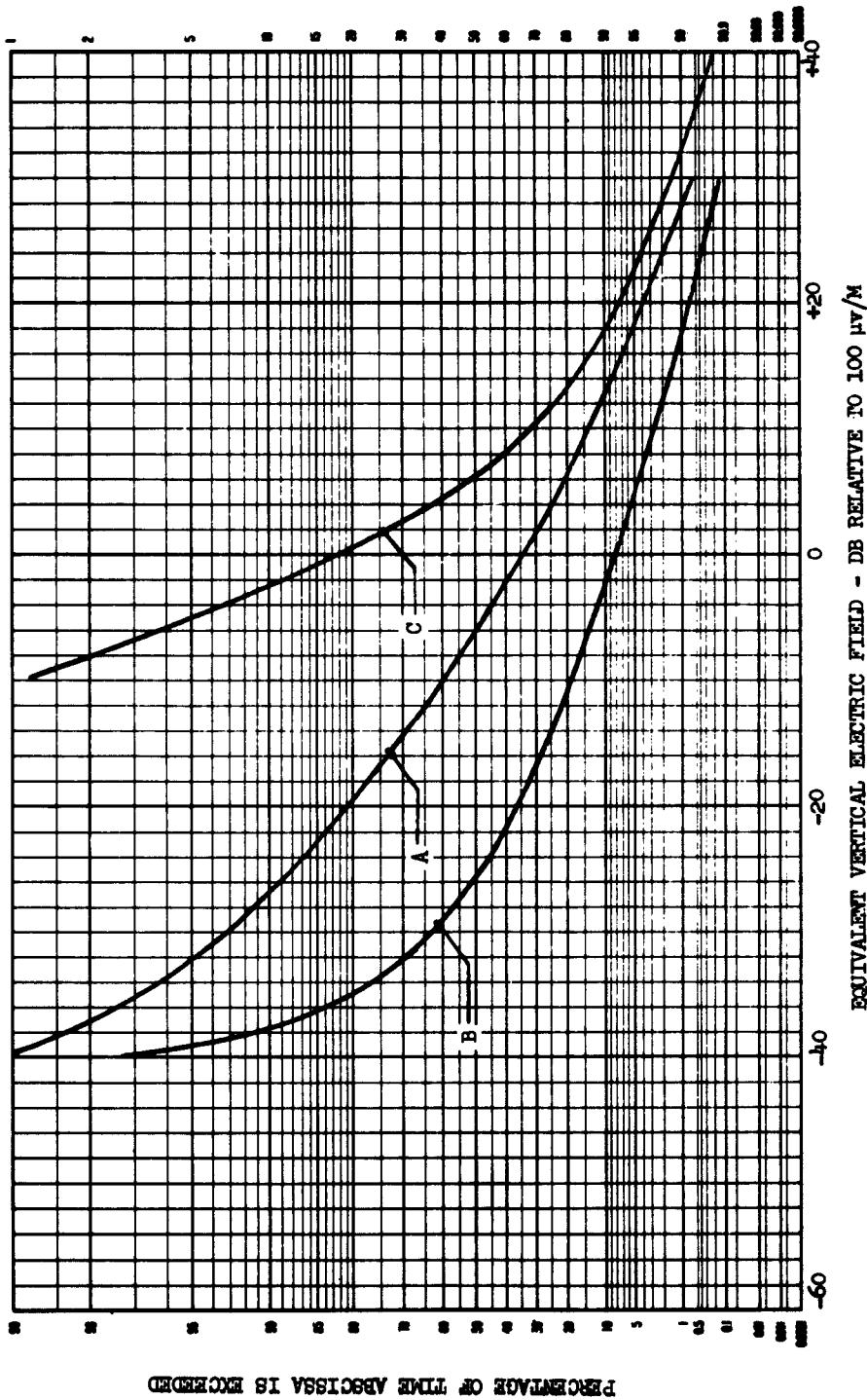


Figure 19. Atmospheric Noise Amplitude Probability Distribution - July 17, 1962

Location: Carlsbad, N.M.
 $f_o = 400$ CPS
 $BW = 40$ CPS
 A 0320 HRS., MST
 B 0345 HRS., MST
 C 1630 HRS., MST

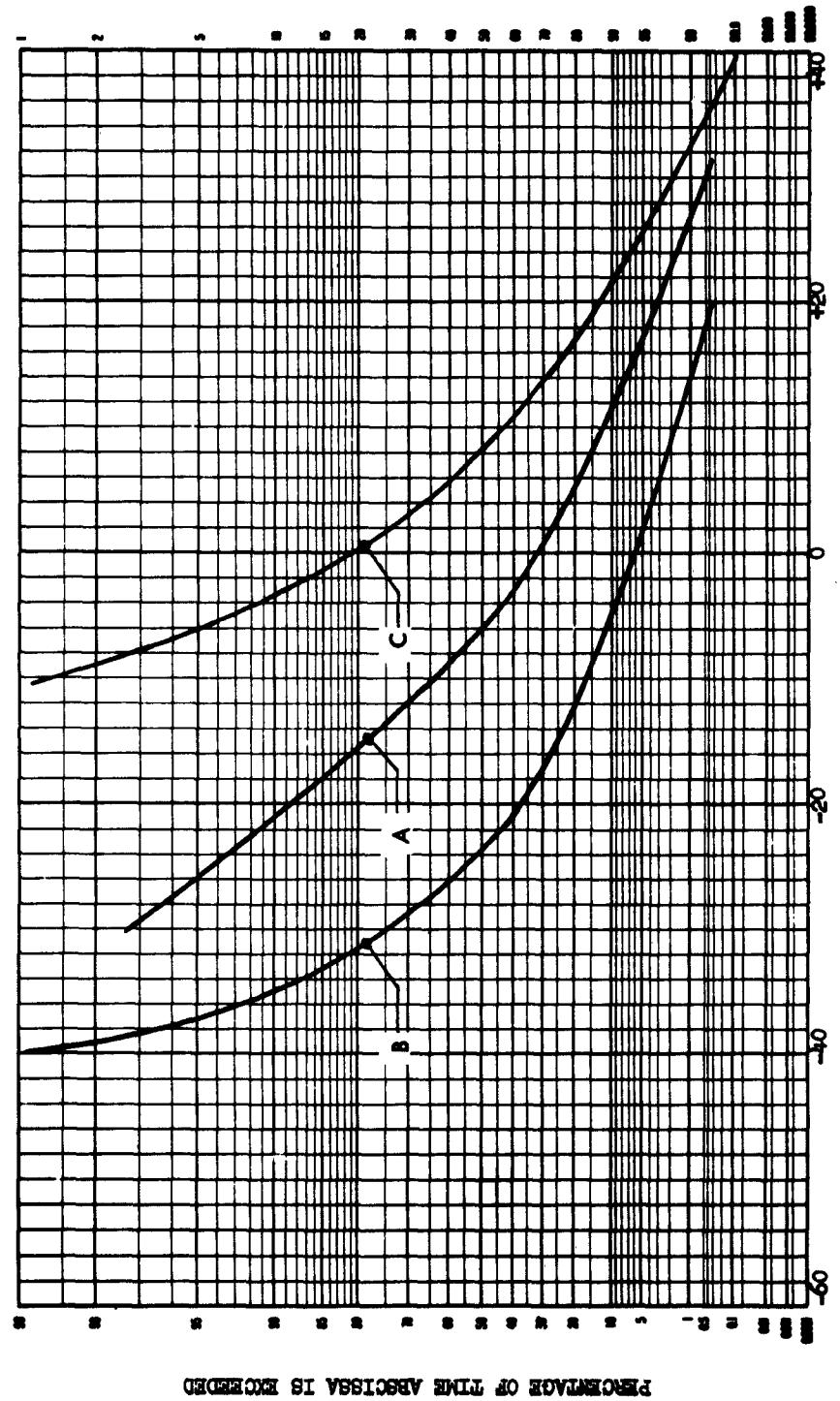


Figure 20. Atmospheric Noise Amplitude Probability Distribution - July 18, 1962

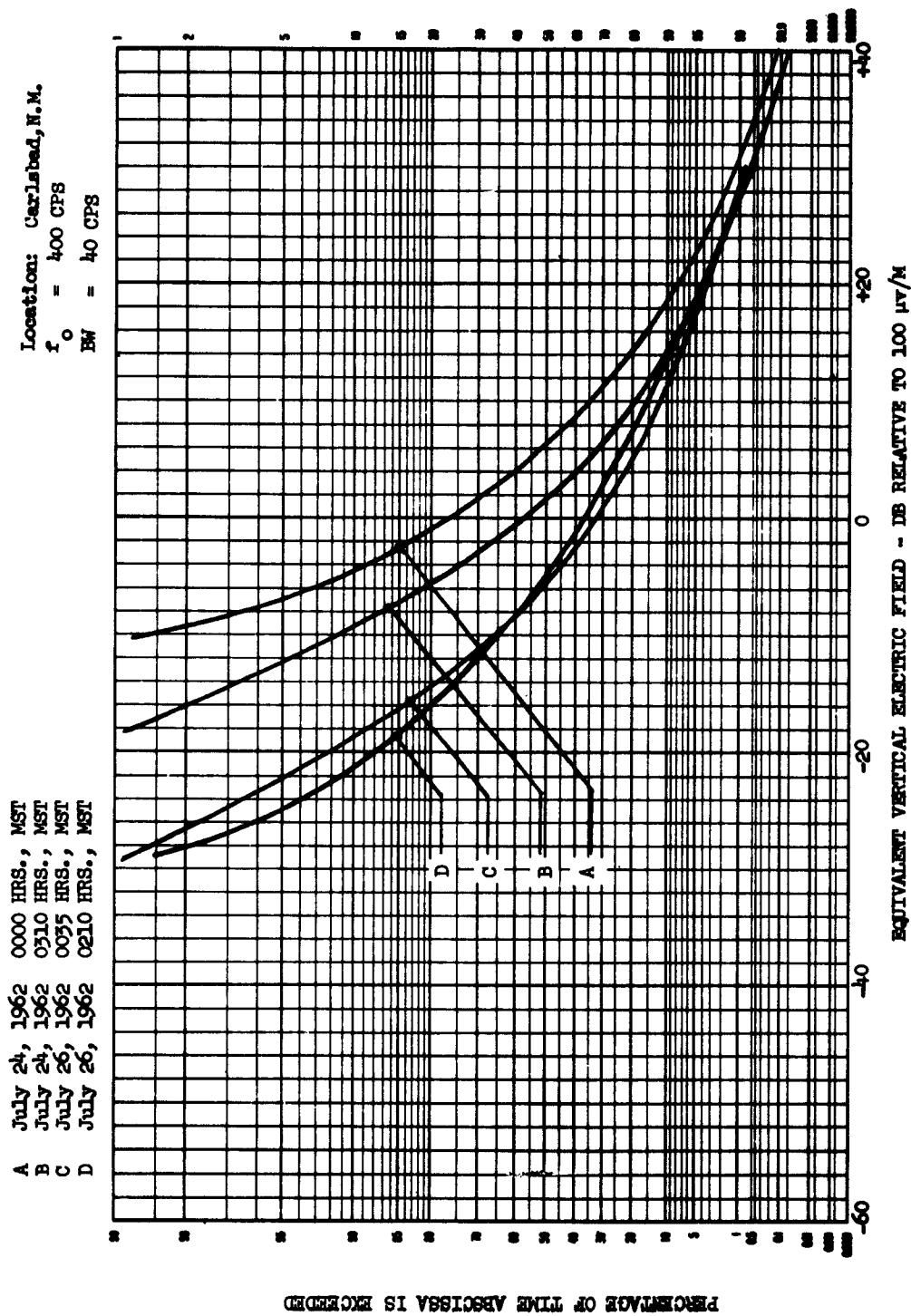


Figure 21. Atmospheric Noise Amplitude Probability Distribution - July 24 and 26, 1962

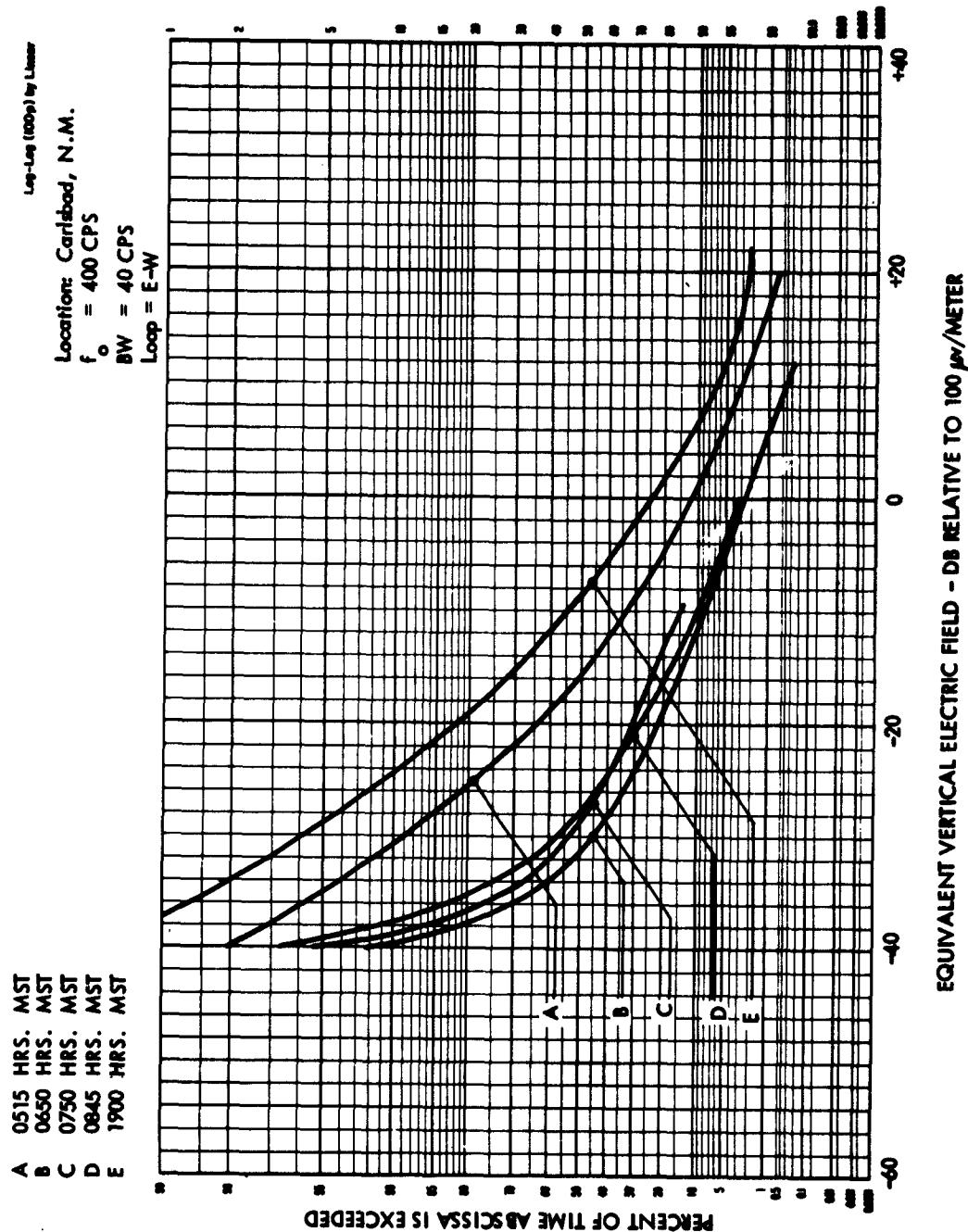


Figure 22. Atmospheric Noise Amplitude Probability Distribution - Oct. 24, 1962

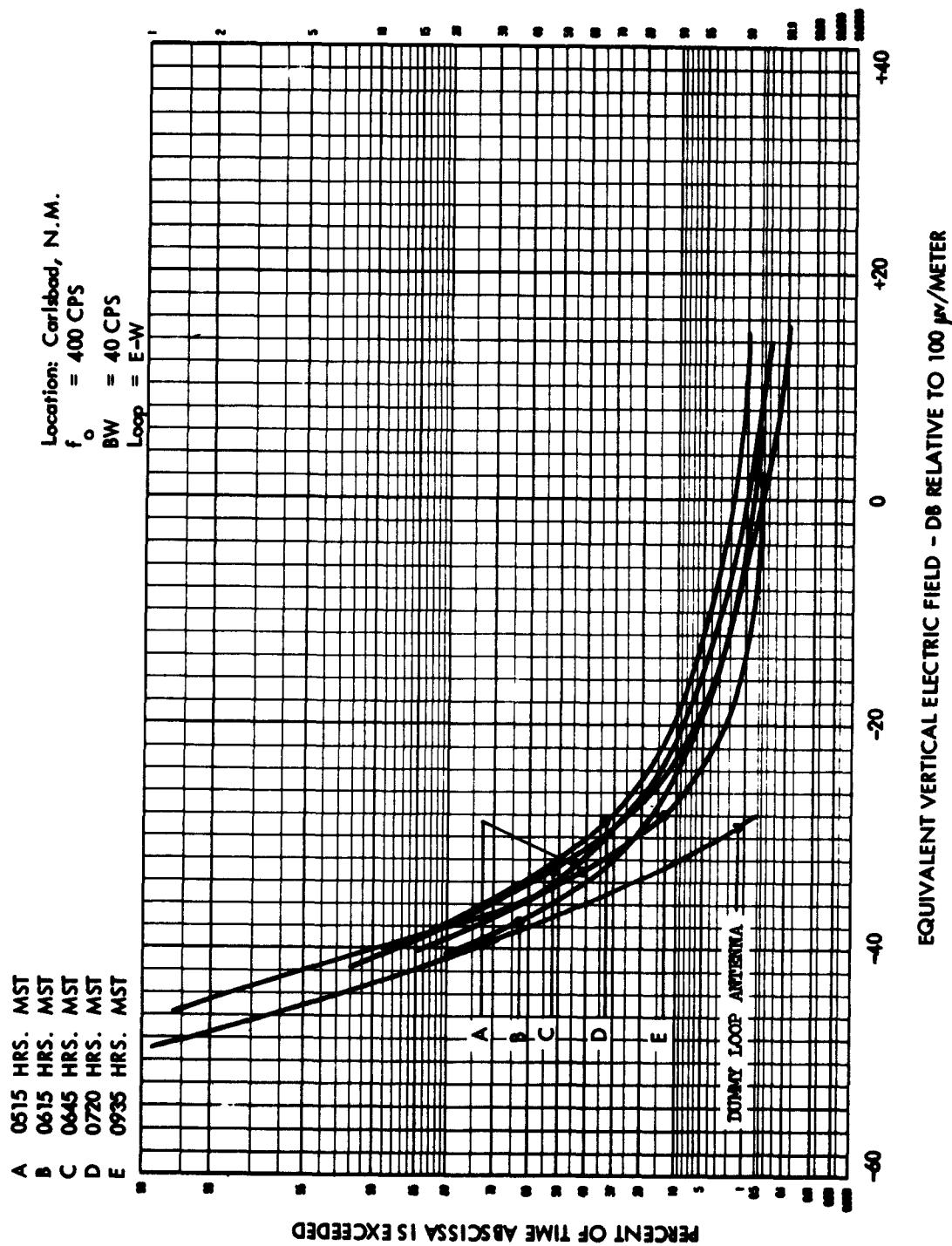


Figure 23. Atmospheric Noise Amplitude Probability Distribution - Oct. 25, 1962

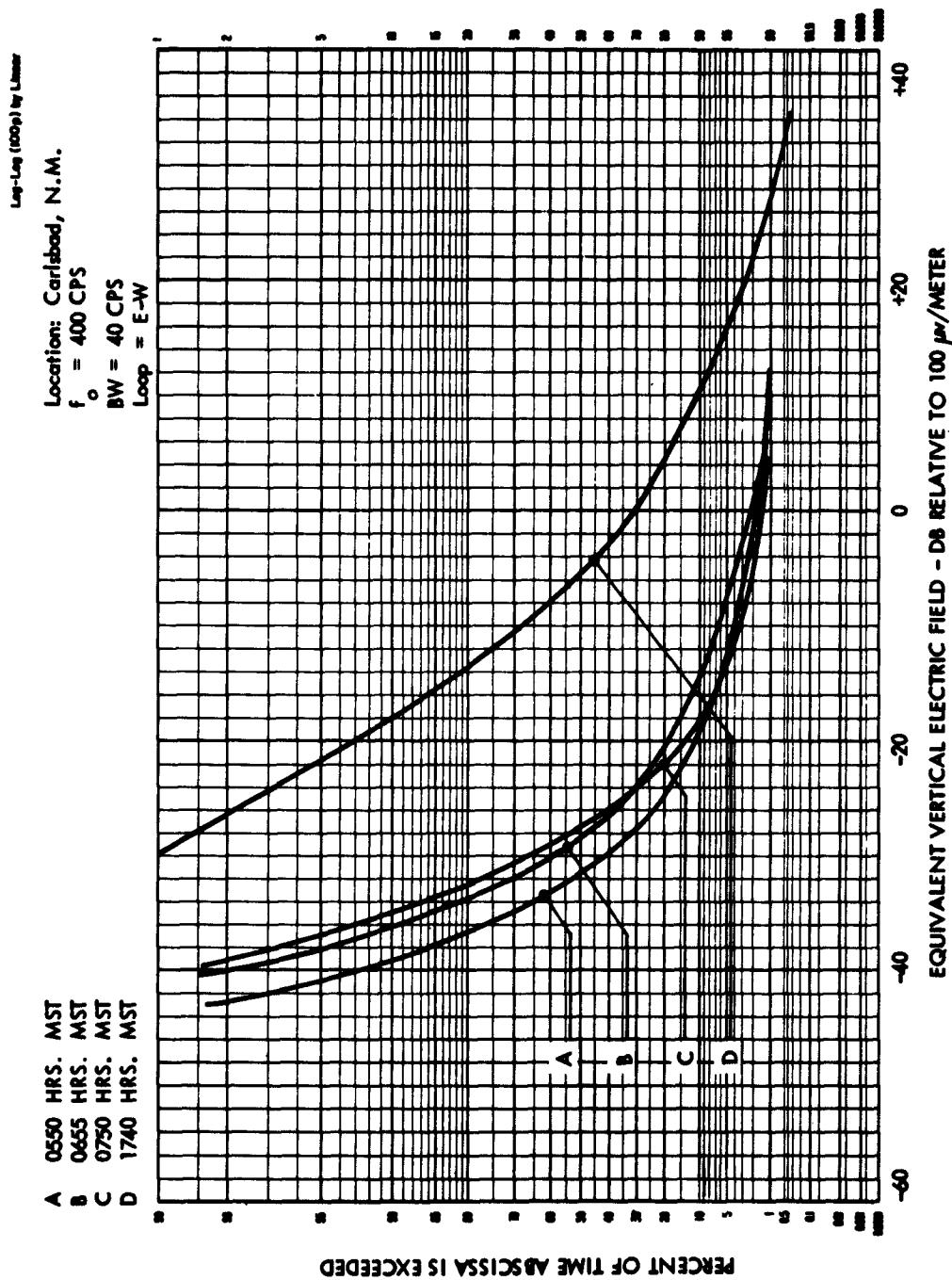


Figure 24. Atmospheric Noise Amplitude Probability Distribution - Oct. 26, 1962

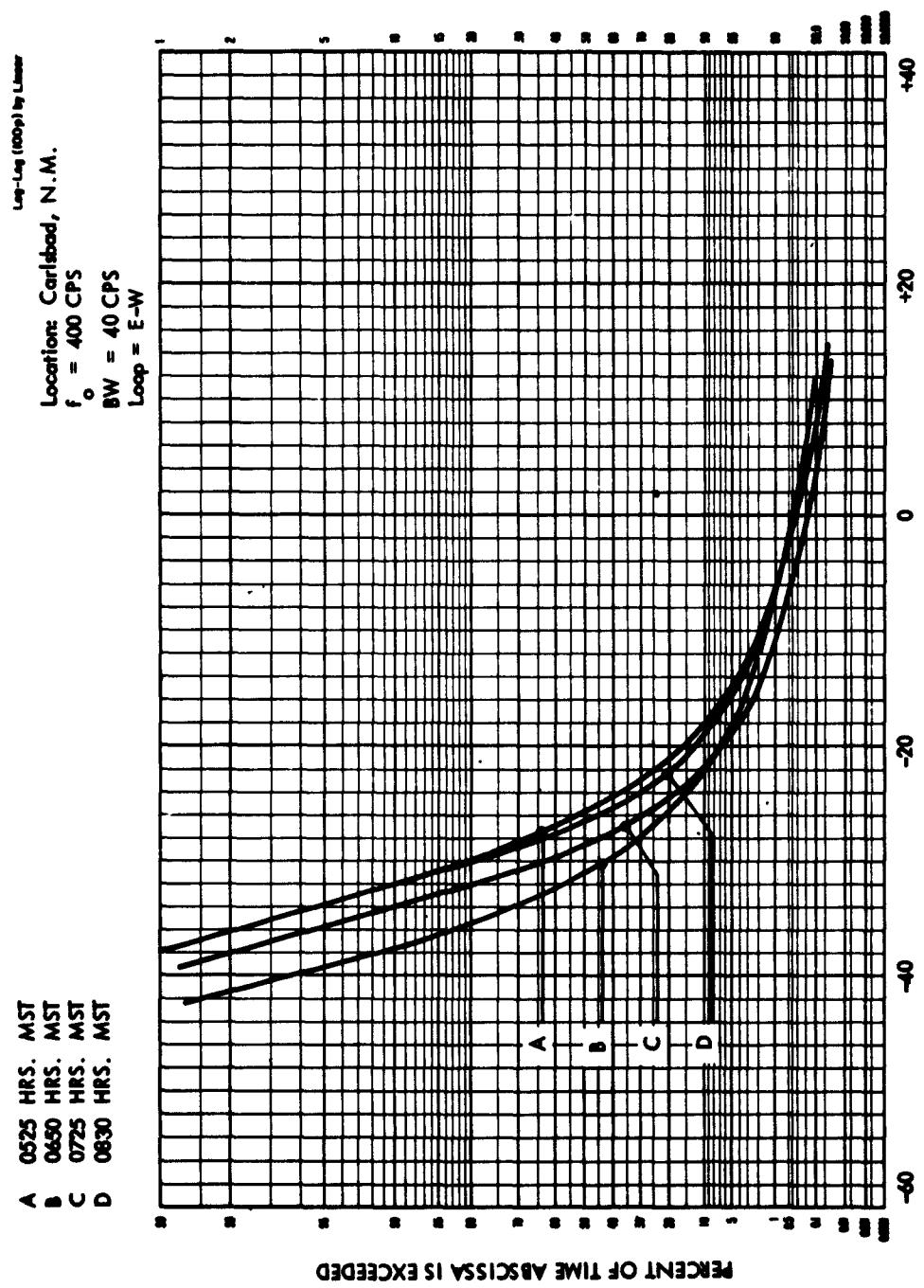


Figure 25. Atmospheric Noise Amplitude Probability Distribution - Oct. 27, 1962

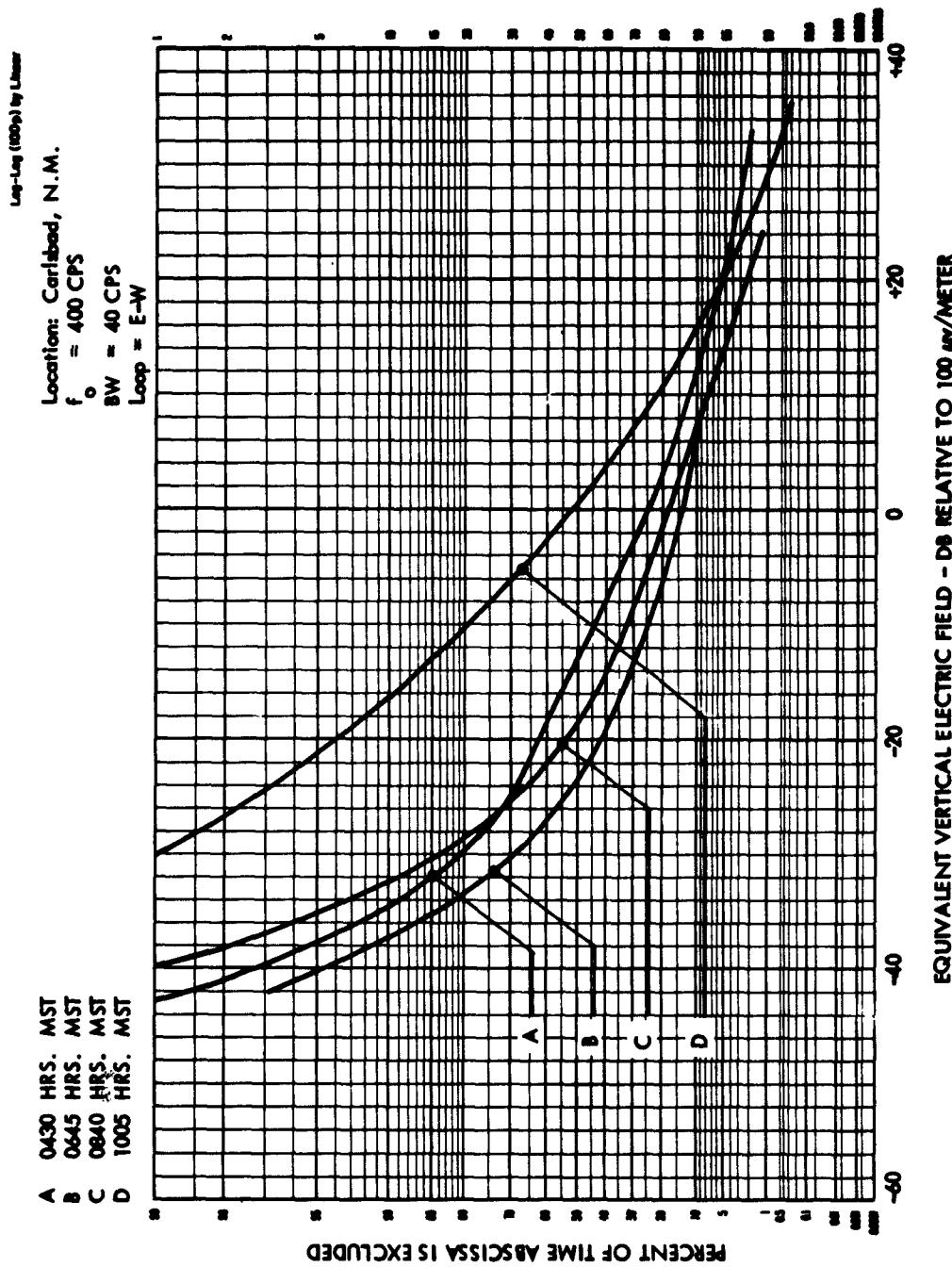


Figure 26. Atmospheric Noise Amplitude Probability Distribution - Oct. 28, 1962

the Caribbean area east of the receiver. With the sun lighting the ionosphere east of the receiver first, the noise from the Caribbean area is attenuated for a considerable period before the signal arriving from the west begins the morning diurnal decrease. Figure 26 is an example of the noise decreasing during the sunrise period and increasing after sunrise. This example is over a 5-1/2 hour period.

4.4 Atmospheric Noise Impulses

The method for totalizing the number of atmospheric noise impulses was described in Section 2.2 and 3.0. Basically, this unit counts the number of noise impulses that exceed the predetermined threshold level, for the ten or 100-second periods.

The APD determines the percent of time the noise exceeds a predetermined threshold, but yields no information as to the number or average width of the impulses. The atmospheric noise impulse count is a measure of the number of impulses that exceed the predetermined threshold. Information as to the average impulse width can be determined from the combination of the two curves.

Figure 27 shows a number of atmospheric noise impulse count distributions. The curves shown reach a maximum value and are arbitrarily discontinued.

Signal reception was best on days with the least number of high level impulses; curves C and D of Figure 27. On October 28 (Figure 27,

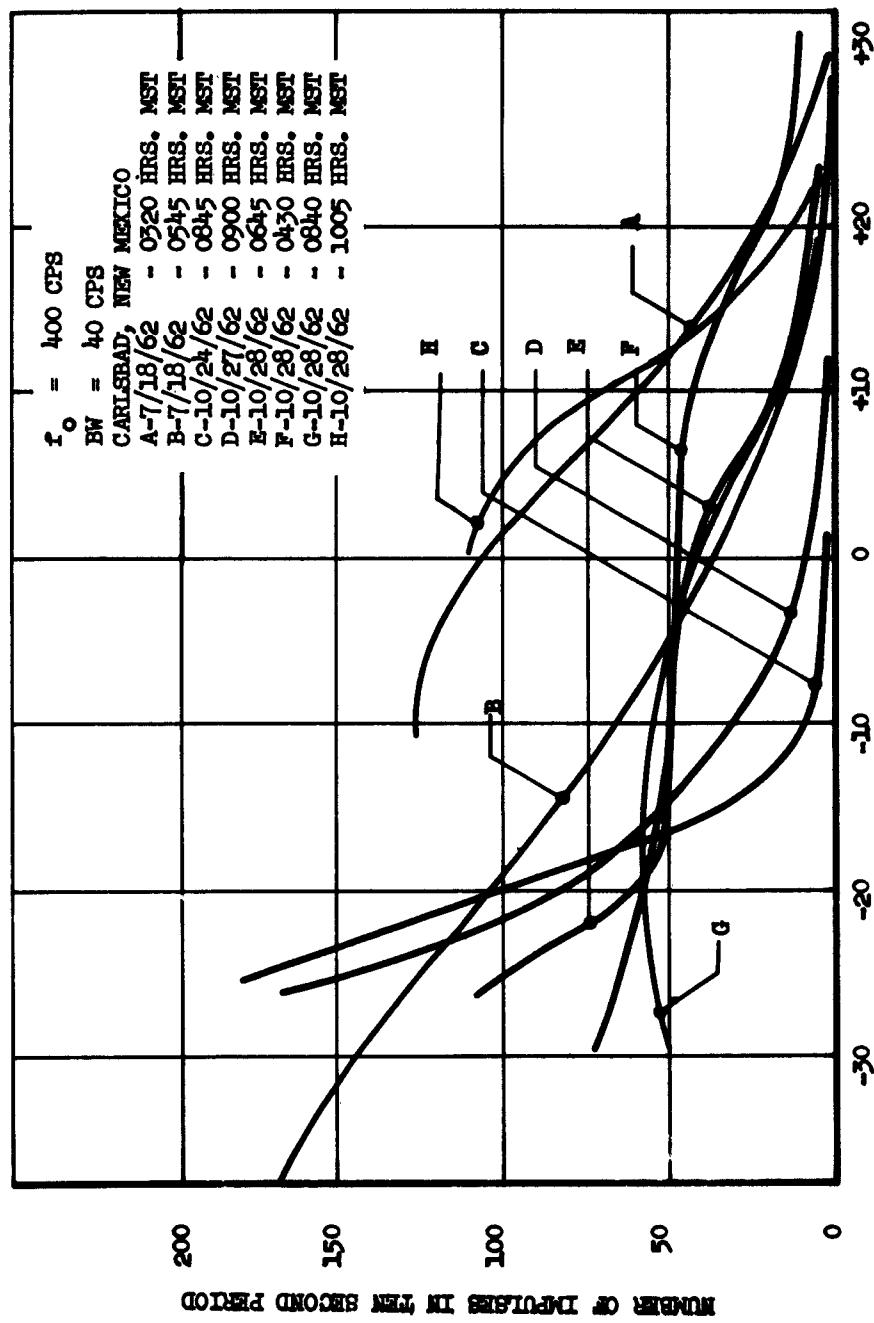


Figure 27. Atmospheric Noise Impulse Count Distribution

curves E, F, G, H), there was visible thunderstorm activity northeast of the Carlsbad area two hours before sunrise. This thunderstorm was traveling in a northeast direction and was not visible by dawn.

Comparing curves E, F, G, and H of Figure 27, note that the impulse count decreases during the sunrise period, but increases after sunrise. Curves E, F, G and H, taken on a stormy day, show that the total number of impulses is greater and the distribution is above the levels shown in curves C and D, which are typical for periods when signal reception was good (Table 2). Additional data must be collected and analyzed before additional conclusions can be drawn.

5.0 CONCLUSIONS

The 400 cps transmission link established between Boron, California, and Carlsbad, New Mexico, has made possible experimental studies of the diurnal night-to-day signal decrease, evolution of a transmission phase measurement technique, and evaluation of phase-lock loop receiver techniques for use in ELF propagation studies. Atmospheric noise data collected during transmission tests has provided a reference level for comparative evaluation of receiver performance.

Signal strength measurements taken during the sunrise period have established the magnitude of the diurnal decrease for a 1300 km transmission path. Although this variation which is approximately 6 db agrees well with analytical predictions the absolute level of the received signal both before and after sunrise is approximately 2 db below the analytical prediction. In the region where ionosphere characteristics determine signal attenuation, reduction of the measured data yields only a single point on the analytically predicted nighttime and daytime signal attenuation curves. For this reason, the rate of attenuation values given as 2.3 db/1000 km for nighttime and 6.0 db/1000 km for daytime conditions in Ref. 1 cannot be revised.

A transmission path phase measurement technique was evolved during the measurements program. Although the data collected to date cannot be used to estimate path phase characteristics equipment requirements and data reduction techniques have been established.

During the program, a phase-lock loop receiver was designed and evaluated. Although only a limited amount of experience was obtained with this unit the data recorded indicates that signal-to-noise improvements proportional to the bandwidth reduction from 1 cps to .25 cps have been realized. It is to be noted that the phase-lock technique in conjunction with a hard-limiter does not provide a significant signal to noise improvement when atmospheric noise conditions are severe. There are indications that some improvement can be made in this area by using more sophisticated signal processing such as a feedback limiter before or after phase detection.

Atmospheric noise data collected during the program provides an increasing store of information that can be used to establish the signal environment that must be used in the design of experiments and equipment.

6.0 RECOMMENDATIONS

It is recommended that the experimental and theoretical investigation of ELF propagation using a 400 cps transmitter be increased in scope to permit an investigation of long range overland propagation phenomena. The objectives of this program would be:

- (1) Precise determination of attenuation rate
- (2) Definition of the ionosphere model
- (3) Observation of propagation path variations, both normal and those associated with SID
- (4) Path phase stability determination

It is recommended that these investigations be carried out by establishing a path the full width of the continental United States. An increase in radiated power of at least 20 db must be obtained if longer range experiments are to be successful. This power increase can only be obtained by increasing the antenna radiation efficiency. To obtain the increased radiation efficiency, it is recommended that an agreement for use of a power transmission line 40-60 miles in length over a low conductivity region be negotiated.

LIST OF SCIENTISTS AND ENGINEERS

Personnel assigned to the project were:

Project Manager: G. R. Dunn

Project Engineer: R. D. Smith

Engineer: P. F. Kuhnle

Engineer: T. M. Georges

Technician: W. R. Howalt

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<p>Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Mass. Rpt. No. AFRL-63-46. EXPERIMENTAL RESEARCH INVESTIGATION OF EXTREMELY LOW FREQUENCY PROPAGATION. Scientific rpt. no. 1, 15 Feb 63, 51p. incl., illus., tables, charts, figures, diagrams, photographs, 5 refs. Unclassified Report.</p> <p>Characteristics of ELF electromagnetic wave propagation were investigated by measuring the characteristics of cw signals transmitted over a 400 cps link established between Boron, California, and Carlsbad, New Mexico, a distance of 1300 km. The work described is a continuation of the investigations carried out under AF 19(604)-7448.</p>	<p>1. Wave transmission, extremely low frequency electromagnetic waves, propagation ionospheric propagation 1. AFRL-63-46, Project AFRL-63-46, Task 4603, Task 4603, Contract AF19(639)-1603</p> <p>II. Space-General Corporation, El Monte, Calif. Smith, R. D.; Kuhne, P. F.; Georges, T. M. Secondary Rpt. No. SEC 212R-4</p> <p>III. Space-General Corporation, El Monte, Calif. IV. Smith, R. D.; Kuhne, P. F.; Georges, T. M. Secondary Rpt. No. SEC 212R-4</p> <p>V.</p>	<p>1. Wave transmission, extremely low frequency electromagnetic waves, propagation ionospheric propagation 1. AFRL-63-46, Project AFRL-63-46, Task 4603, Task 4603, Contract AF19(639)-1603</p> <p>II. Space-General Corporation, El Monte, Calif. Smith, R. D.; Kuhne, P. F.; Georges, T. M. Secondary Rpt. No. SEC 212R-4</p> <p>V.</p>
<p>Propagation measurements were carried out during July and October 1962. Signal strength, received and transmitted signal phase, and atmospheric noise were recorded. Data reduction and analysis showed that received values of signal strength were 2 db less during nighttime and 4 db less during daytime than the values predicted by analytical studies carried out during the previous contract. Data reduction and analysis of the recorded phase data showed that more stable reference signal sources are required at transmitter and receiver. The form of the record obtained over a link which had approximately a 6 db signal to noise ratio in a 1 cps band indicates that a useful technique has been evolved.</p> <p>Atmospheric noise data was recorded for all transmission periods. This data is presented in the form of amplitude probability distributions and impulses per unit time distributions.</p>	<p>Propagation measurements were carried out during July and October 1962. Signal strength, received and transmitted signal phase, and atmospheric noise were recorded. Data reduction and analysis showed that received values of signal strength were 2 db less during nighttime and 4 db less during daytime than the values predicted by analytical studies carried out during the previous contract. Data reduction and analysis of the recorded phase data showed that more stable reference signal sources are required at transmitter and receiver. The form of the record obtained over a link which had approximately a 6 db signal to noise ratio in a 1 cps band indicates that a useful technique has been evolved.</p> <p>Atmospheric noise data was recorded for all transmission periods. This data is presented in the form of amplitude probability distributions and impulses per unit time distributions.</p>	<p>Propagation measurements were carried out during July and October 1962. Signal strength, received and transmitted signal phase, and atmospheric noise were recorded. Data reduction and analysis showed that received values of signal strength were 2 db less during nighttime and 4 db less during daytime than the values predicted by analytical studies carried out during the previous contract. Data reduction and analysis of the recorded phase data showed that more stable reference signal sources are required at transmitter and receiver. The form of the record obtained over a link which had approximately a 6 db signal to noise ratio in a 1 cps band indicates that a useful technique has been evolved.</p> <p>Atmospheric noise data was recorded for all transmission periods. This data is presented in the form of amplitude probability distributions and impulses per unit time distributions.</p>